POLITECNICO DI TORINO

Corso di Laurea Magistrale in Ingegneria Biomeccanica

Tesi di Laurea Magistrale

Comparative Analysis of THUMS Versions for Safety Applications

Relatore: Prof. Lorenzo Peroni

Correlatori: Prof. Alessandro Scattina

Prof.ssa Martina Scapin

Candidata: Repetto Fabia

Matricola: s292264

Anno Accademico 2024/2025

Table of Contents

1. Introduction

The aim of this study is to conduct a comparative analysis of the Toyota Human Model for Safety (THUMS) in its three latest versions—Version 4, Version 5, and Version 6 [1]—using finite element simulations in LS-DYNA. The study focuses on evaluating key differences in anatomical accuracy, injury prediction capability, and computational efficiency across these versions.

Version 4 is characterized by a detailed anatomical structure, including internal organs, which enhances injury analysis. Version 5 simplifies the anatomical representation but introduces active muscle modeling, allowing the simulation of pre-impact occupant postures. Version 6 integrates both features, combining the detailed anatomy of Version 4 with the muscle activation capabilities of Version 5, resulting in a more advanced human body representation.

To assess these differences, three simulation scenarios were developed, ensuring that each model version is tested under the same impact conditions. In first and second scenario, the study investigates the improvements in injury prediction accuracy and postural response. Additional tests were performed using Versions 5 and 6 with muscle activation enabled, which improves postural control and allows the model to maintain a physiological posture when subjected to external forces, increasing the realism of the simulations.

Beyond automotive crash scenarios, this study also explores the applicability of THUMS in non-automotive safety contexts, such as injury prevention in everyday life. To achieve this, in the third simulation, the model was repositioned from a seated to a standing posture and subjected to a fall simulation, assessing its potential use in research beyond vehicle safety.

2. Road Traffic Injuries Concern

Road traffic injuries are the leading cause of death and disability worldwide, particularly among young people aged 5 to 29, according to the World Health Organization (WHO). Each year, approximately 1.35 million people die from road traffic accidents, and 20 to 50 million suffer non-fatal injuries. These injuries represent a significant public health challenge with severe consequences for individuals and communities [2].

Addressing road traffic injuries requires a multi-faceted approach, involving governments, law enforcement, healthcare systems, the automotive industry, and public awareness. Research and development play a crucial role in improving road and vehicle safety, with automotive researchers frequently collaborating with manufacturers to design safer vehicles and enhance occupant protection. Virtual crash tests and physical crash tests are two complementary approaches used in automotive research to assess the safety performance of vehicles.

Physical crash tests, which use standardized crash test dummies, are essential for meeting regulatory safety requirements and provide real-world data. These dummies offer key advantages, such as ensuring consistency across tests, being widely accepted by regulatory agencies, and providing valuable historical data for safety comparisons. On the other hand, virtual crash tests offer several advantages over physical tests, particularly with the introduction of advanced simulation tools like Human Body Models (HBMs). These models predict and analyze the impact of accidents on the human body through virtual crash scenarios. HBMs provide biomechanical realism, injury prediction, customization for various populations, and dynamic response analysis during crashes. Moreover, virtual crash tests allow for the repetition of simulations with small variations in the crash scenario, such as changes in vehicle speed or occupant position, at a fraction of the cost of conducting multiple physical tests [3] [4].

By combining both physical and virtual crash testing methods, a more comprehensive understanding of a vehicle’s crash performance can be achieved. This integrated approach significantly advances vehicle safety, contributing to the reduction of injuries and fatalities in road accidents.

3. Human Body Models (HBMs)

HBMs are computational models that simulate the biomechanical behaviour of the human body in multiple scenarios.

The primary objective of HBMs is to assess and forecast how the human body reacts to external forces. One of the key capabilities of HBMs is their ability to predict injuries to different body regions, based on the applied forces and impact conditions. They are used by engineers and designers to develop safer products, improve injury prevention strategies, and optimize performance across different application fields. HBMs are mainly used in automotive safety research to assess the impact of vehicle crashes on occupants; in sports biomechanics to study injury mechanisms and design protective equipment; and in biomedical field for medical device design and virtual surgery planning.

HBMs include detailed representations of human anatomy, including the skeletal structure, muscles, ligaments, tendons, internal organs, and soft tissues. The level of detail within these models can vary significantly, basing on the specific application and requirements.

The body is divided into six main segments (head, neck, chest, abdomen, pelvis, extremities). The movements and the interactions between adjacent body segments are simulated through joints and articulations. Different materials are assigned to the different anatomical structures to replicate their mechanical properties. The material properties are based on experimental data obtained from studies on cadaver and biomechanical research.

HBMs can be customized to represent specific demographics, including age, gender, and body size. This customization enables a more precise evaluation of injury risk across various populations [3].

Ongoing progress in computational modeling, imaging technologies, and material science contribute to the continuous improvement of HBMs. Nowadays, the world's most advanced virtual HBM is THUMS [1], which will be discussed in more detail in the following chapter.

4. THUMS (Toyota HUman Model for Safety)

4.1. Overview and Development History

Since 1997, Toyota has spent more than 20 years refining and improving the THUMS, with the ultimate goal of achieving zero road traffic fatalities. THUMS is a human body finite element model jointly produced by Toyota Motor Corporation (TMC) and Toyota Central R&D Labs., Inc [1].

It is the first virtual HBM software in the world capable of simulating the entire human body. Toyota engineers manually created three-dimensional meshes to replicate the complex shapes of the human body and programmed the mechanical properties of each component, including bones and internal organs.

Compared to the physical dummies, THUMS is able to analyze collision-related injuries in more detail, because it precisely designs the shapes and strength of the human body by considering both gender, different ages and body sizes [5].

During years, different versions have been developed, as shown in *Figure 1* below.

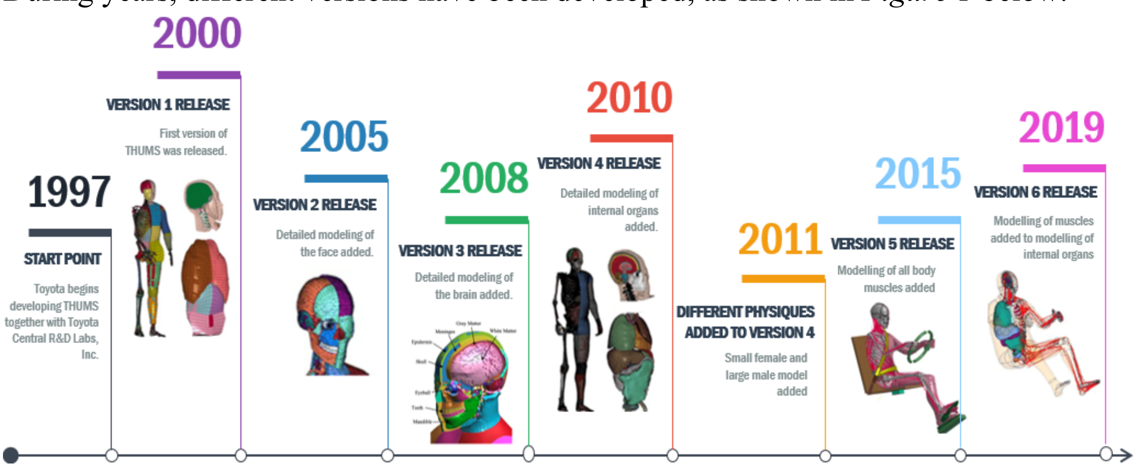


Figure 1 – THUMS development over years

THUMS *Version 1* was released in 2000 and recreated body's shape, bone strength and dermal tenacity. Brain and internal organs were simplified as solid parts, with homogeneous material properties. Version 1 was made up of 80,000 finite elements and only considered a male body (175cm, 77kg).

The female model was launched with *Version 2,* released in 2005. This version included a detailed face mapping, which was not present in the previous model.

In 2008, *Version 3* of THUMS introduced a detailed model of the brain, including white matter, grey matter, and cerebral spinal fluid. Additionally, the version improved joint and soft tissue models, which allowed for a more precise representation of body movements during impacts.

THUMS *Version 4* (2010) added detailed models of internal organs, enabling analysis of injuries to a wider range of body regions. In the creation of Version 4, TMC collaborated with external research institutions, such as universities, and utilized advanced high-precision computed tomography (CT) scanning technology. By creating precise models of various internal organs, as well as the positions of and relations between those organs, TMC created a virtual human model containing approximately 14 times more details than the previous version.

Version 4 included three different body sizes (AM50, AF05, and AM95), that are still used nowadays as standard classification:

- AM50, corresponding to a 50th-percentile adult male, with a height of 179 cm and weight of 79 kg.
- AF05, corresponding to a 5th-percentile adult female, with a height of 153 cm and weight of 49 kg.
- AM95, corresponding to and a 95th-percentile adult male, with a height of 188 cm and weight of 106 kg.

Version 5 (2015) returned to the simplified anatomy of Version 3 but introduced full-body muscular activation to better mimic occupant behaviour before and during a crash. This new feature allows the model to simulate human postural states, such as how the body might naturally adjust or brace itself before impact, as well as how muscles respond during the collision. The ability to simulate these dynamic muscle responses significantly improves the realism and accuracy of the injury risk analysis, making the model more representative of real-life human reactions in crash scenarios.

The last version, *Version 6*, was developed by incorporating the muscle models of Version 5 into the detailed anatomy of Version 4. This combination provides a more accurate representation of muscle dynamics and their interactions with bones and soft tissues, improving the overall injury prediction.

The level of biofidelity has increased linearly across the different versions, expanding the range of possible simulations, as reported in *Figure 2* and *Table 1*. From a computational perspective, Versions 4 and 6 exhibit a higher level of detail and complexity, while Version 5 adopts a more simplified structure. The comparison of FEM Data is detailed in *Table 2* [6] [7] [8].

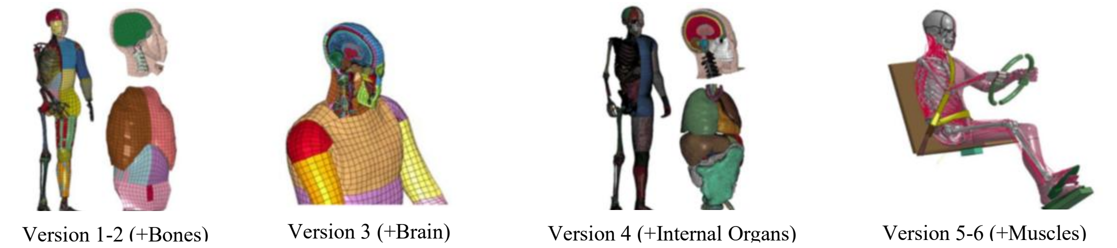


Figure 2- Improvement of biofidelity over different THUMS versions
THUMS AM50 V4.1 Documentation (PDF). TOYOTA MOTOR CORPORATION and TOYOTA CENTRAL R&D LABS., INC

	Version 1-2	Version 3	Version 4	Version 5	Version 6
Bone fracture	Y	Y	Y	Y	Y
Brain injury	N	Y	Y	Y	Y
Organ injury	N	N	Y	Y	Y
Muscle effect	N	N	N	Y	Y

Table 1- Simulation capabilities across different THUMS versions

	Version 4 AM50	Version 5 AM50	Version 6 AM50
Elements	1 921 764	285 792	1 925 520
Solid	1 466 112	146 280	1 466 148
Shell	449 934	122 052	450 058
Seatbelt	5 398	4 422	7 152
Beam	204	12 798	1 970
Others	116	240	192
Node	762 997	185 897	766 459
Part	1293	416	2 213
Time Step [s]	4.0E-7	5.4E-7	4.0E-7

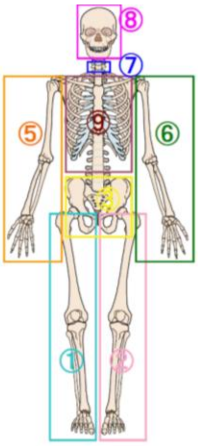
Table 2 - FEM Data Comparison between different versions

4.2. Common Features of THUMS Versions

THUMS versions assume the following units:

- Time: second (s)
- Length: millimeter (mm)
- Weight: tonne (ton)
- Force: newton (N)

All versions use the same entity ID numbering system, as illustrated in Figure 3.



No.	Body Region	Numbering
1	Right Lower Extremity	8100000
2	Left Lower Extremity	8200000
3	Abdomen and Pelvis	8300000
4	Internal Organs	8400000
5	Right Upper Extremity	8500000
6	Left Upper Extremity	8600000
7	Neck	8700000
8	Head	8800000
9	Thorax	8900000
10	Muscle	7000000

Figure 3- Numbering of entities IDs in THUMS
THUMS AM50 V4.1 Documentation (PDF). TOYOTA MOTOR CORPORATION and TOYOTA CENTRAL R&D LABS., INC

Figure 4 shows the entire view of the current THUMS family; the average size male model (AM50), the small size female model (AF05) and the large size male model (AM95) in occupant posture, respectively.

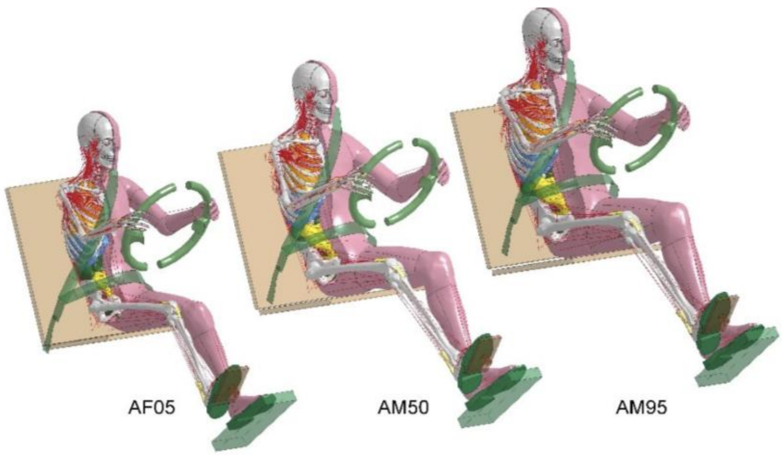


Figure 4- THUMS variety of body physiques
THUMS AM50 V4.1 Documentation (PDF). TOYOTA MOTOR CORPORATION and TOYOTA CENTRAL R&D LABS., INC

For what concern the development process, it is a comprehensive and meticulous process that involves four main steps:

I. Acquisition of medical imaging data.
II. Finite Element Modeling (FEM) of body parts.
III. Integration into whole body model, meticulously managing interconnections and interactions among body parts.
IV. Definition of material property of each body component [6][7][8].

4.3. THUMS Version 4

THUMS Version 4 is defined by a high detail in the modeling of all body parts, with no geometrical simplification.

4.3.1. Methodology of Data Acquisition

A dataset of a 39-year old male (173 cm tall, 77.3 kg, with a BMI of 25.8) was selected for the AM50 model. The head and extremity geometries were initially based on Version 3 but underwent refinement to achieve a finer mesh. Torso parts were acquired through scanned data and subsequently converted into Standard Triangulated Language (STL) format polygons for each body and tissue part [6].

4.3.2. Anatomical Structures Description

4.3.2.1. Head Model

The primary elements of the head model encompass the cerebellum, brainstem, cerebrospinal fluid (CSF), cerebrum (inclusive of white and gray matter), meninges, epidermis, skull, eyeball, teeth, and mandible, as illustrated in *Figure 5.*

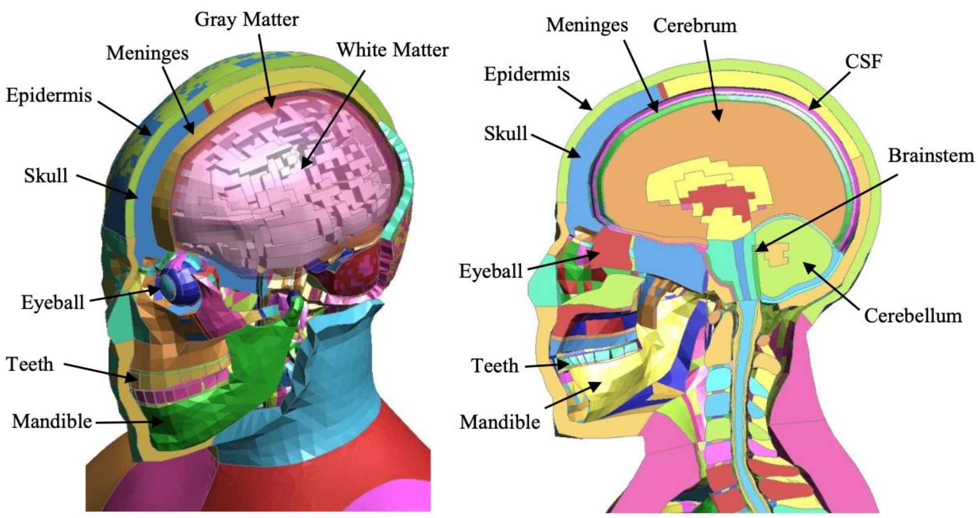


Figure 5- THUMS v4: Head model
THUMS AM50 V4.1 Documentation (PDF). Copyright MOTOR CORPORATION and TOYOTA CENTRAL R&D LABS., INC

4.3.2.2. Torso model

Torso model includes both hard and soft tissues.

The main hard tissues *(see Figure 6)* reproduced are ribs, sternum, spine, clavicles, scapulas, sacrum and pelvis; while the connective tissues replicated are costal cartilages, intervertebral discs, pubic symphysis and ligaments.

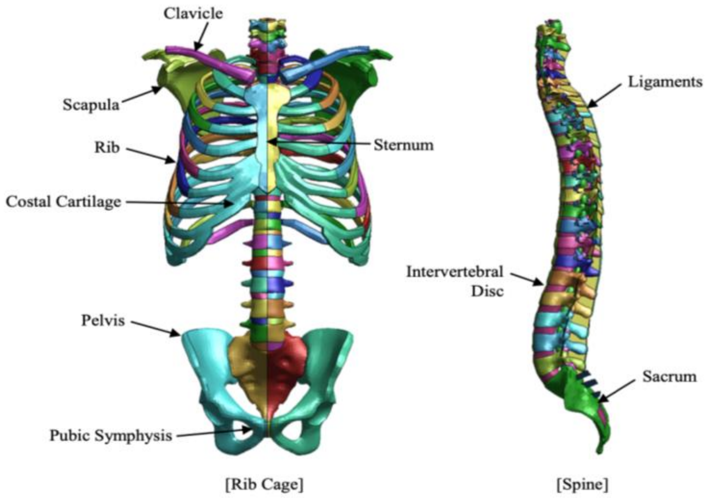


Figure 6 - THUMS v4: Torso model (skeletal part)
THUMS AM50 V4.1 Documentation (PDF). TOYOTA MOTOR CORPORATION and TOYOTA CENTRAL R&D LABS., INC

Inside the torso model, internal organs are reproduced as individual FE parts.
The organ tissues included are figured in *Figure 7* and are as follows: heart, lungs, liver, kidneys, spleen, pancreas, gall bladder, bladder, esophagus, stomach, duodenum, small intestine, and large intestine.

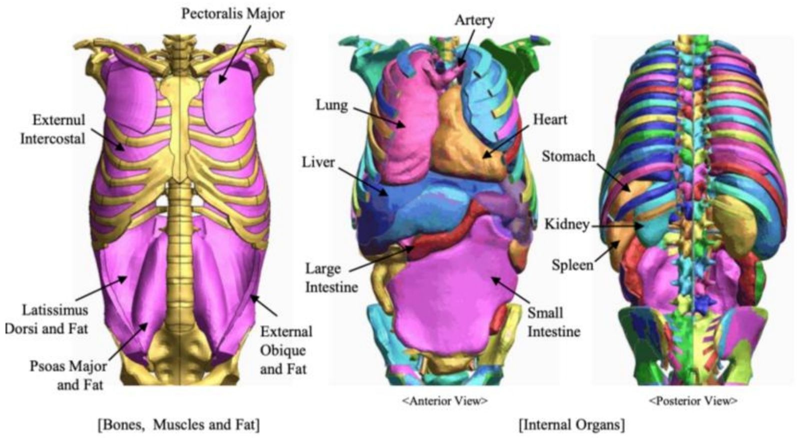


Figure 7- THUMS v4: Torso model (soft tissue parts)
THUMS AM50 V4.1 Documentation (PDF). TOYOTA MOTOR CORPORATION and TOYOTA CENTRAL R&D LABS., INC

4.3.2.3. Extremity models

The upper and lower extremities include all the major bones as shown in *Figure 8.* These long bones are composed of both cortical and trabecular bone types. Surrounding the skeletal components are the flesh parts, which primarily correspond to the extensor and flexor muscles.

Joints are modeled as bone-to-bone connections with ligaments. No kinematic joint element is used.

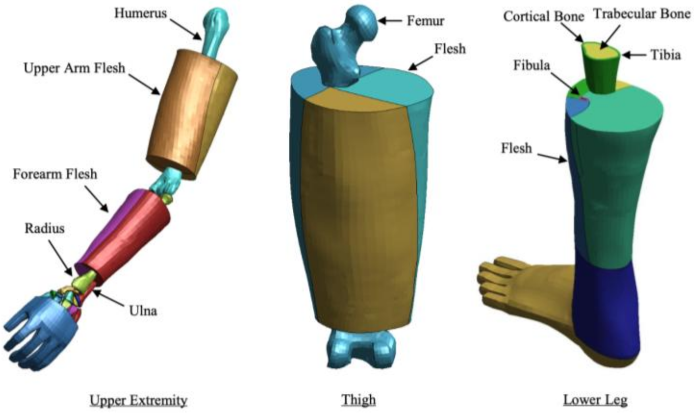


Figure 8 -THUMS v4: Extremities models
THUMS AM50 V4.1 Documentation (PDF). TOYOTA MOTOR CORPORATION and TOYOTA CENTRAL R&D LABS., INC

4.3.3. Integration into whole body model

The entire body model *(see Figure 9)* was created by smoothly integrating individual component models, ensuring mesh continuity and eliminating geometric discontinuities. Tetrahedral elements were utilized in the joint regions to facilitate easier remeshing, whereas hexahedral elements were employed in the remaining areas.
The whole-body model contains the FEM attributes listed in *Table 3* [6].

Version	Elements	Node	Part	Time Step [s]
4 AM50	1 921 764	762 997	1293	4.0E-7

Table 3 - FEM Data Version 4

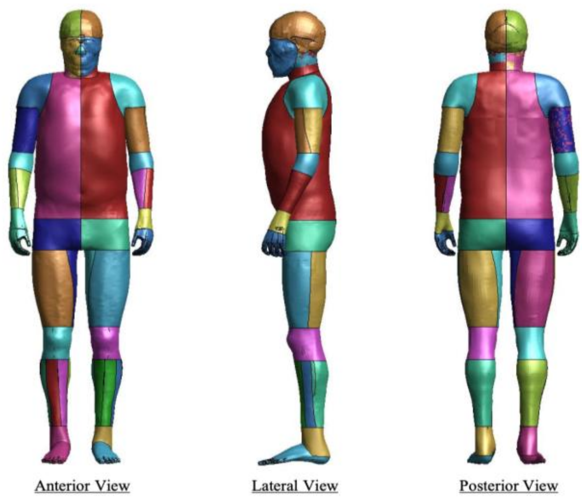


Figure 9 - THUMS v4: Whole Body model (pedestrian)
THUMS AM50 V4.1 Documentation (PDF). TOYOTA MOTOR CORPORATION and TOYOTA CENTRAL R&D LABS., INC

4.3.4. Material Properties

The skeletal components were modeled with elasto-plastic properties. Soft tissues were represented using hyperelastic materials. Ligaments and tendons exhibit low stiffness under small elongations and high stiffness when significantly elongated. Solid organs, including the liver and kidneys, were considered to have incompressible mechanical properties, which are accurately captured by hyperelastic material models. Hyperelastic materials were used to represent skin and flesh. Hollow organs, such as the lungs and intestines, were characterized by compressible mechanical properties and were modeled using low-density foam materials. Despite being a hollow organ, the heart, with its thick muscular walls and internal blood content, was treated as having highly incompressible mechanical properties [6].

The main materials used in LS-DYNA model are listed in *Table 4*.

Model Component	Material Type	LS-DYNA Material
Bone Model	Cortical Bone	MAT_24: MAT_PIECEWISE_LINEAR_PLASTICITY
	Spongeous Bone	MAT_105: MAT_DAMAGE_2
Muscles and Ligaments	Muscles	MAT_B01: SEATBELT
		MAT_S02: DAMPER_VISCOUS
		MAT_S15: SPRING_MUSCLE
	Ligaments	MAT_181: MAT_SIMPLIFIED_RUBBER/FOAM
Head Model	Skull	MAT_81: MAT_PLASTICITY_WITH_DAMAGE
		MAT_105: MAT_DAMAGE_2
	Brain	MAT_61: MAT_KELVIN-MAXWELL_VISCOELASTIC
	CSF	MAT_1: MAT_ELASTIC_FLUID
	Meninges	MAT_1: MAT_ELASTIC
	Skin	MAT_181: MAT_SIMPLIFIED_RUBBER/FOAM
Spine Model	Nucleus	MAT_12: MAT_ISOTROPIC_ELASTIC_PLASTIC
	Anulus	MAT_83: MAT_FU_CHANG_FOAM
	Spinal Cord	MAT_6: VISCOELASTIC
Organs	Solid Organs	MAT_181: MAT_SIMPLIFIED_RUBBER
	Hollow Organs	MAT_34: MAT_FABRIC
		MAT_1: MAT_ELASTIC_FLUID
	Lungs	MAT_57: MAT_LOW_DENSITY_FOAM

Table 4- THUMS v4: LS-DYNA Materials

4.4. THUMS Version 5

Version 5 is an anatomically simplified version compared to Version 4, to which the muscle model is added.

4.4.1. Methodology of Data Acquisition

The geometry data for THUMS AM50 Version 5.03 was not obtained from a single male subject. Instead, it was determined by referencing the following sources:

- Whole body shapes: Based on anthropometric and geometry data for mid-size adult males reported by Schneider et al. (1983).
- Skeletal parts: Derived from the commercially available dataset by Viewpoint Data Lab (USA).
- Brain and internal organs: Based on high-resolution CT and MRI images from a human male cadaver (180 cm height, 90 kg weight) as provided by the Visible Human Project Data (National Institute of Health, USA).
- Ligaments, tendons, and muscles: Referenced from anatomical texts, including works by Agur et al. (2005) [7].

4.4.2. Anatomical Structures Description

4.4.2.1. Head model

The head/brain model *(see Figure 10)* comprises three primary components: the skull, brain, and skin. The brain model is further divided into: cerebrum, cerebellum, and brainstem. Distinct representations for white matter, gray matter, and cerebral spinal fluid (CSF) are included.

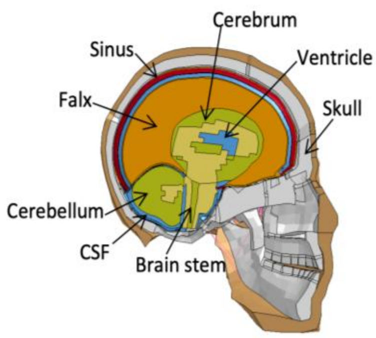


Figure 10 - THUMS v5: Head
THUMS AM50 V5.3 Documentation (PDF). TOYOTA MOTOR CORPORATION and TOYOTA CENTRAL R&D LABS., INC

4.4.2.2. Torso Model

The thorax model includes from 1st to 12th ribs (left and side), sternum, and rib cartilages. It also includes each vertebra of the thoracic and lumbar spines. Intercostal muscles are represented with shell elements.
Inside the skeletal structure, the Torso includes all main internal organs (see *Figure 11)*, both solid (like the liver, spleen, pancreas, and kidneys) and hollow (including the stomach, intestines, aorta, vena cava, trachea, and esophagus).

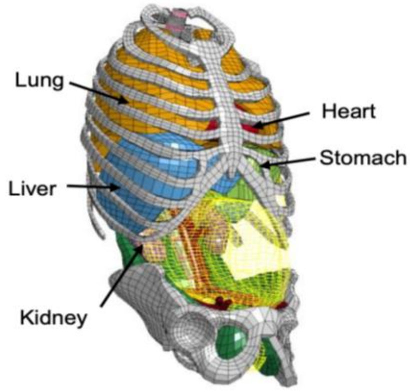


Figure 11 - THUMS V5: Internal Organs model
THUMS AM50 V5.3 Documentation (PDF). TOYOTA MOTOR CORPORATION and TOYOTA CENTRAL R&D LABS., INC

4.4.2.3. Extremity Models

The extremity models include all major skeletal structures. A key improvement over the previous version is the introduction of a detailed muscle model. As an example, *Figure 12* illustrates the shoulder model, which includes major muscle groups such as the deltoid, biceps brachii, pectoralis major, trapezius, and intercostal muscles.

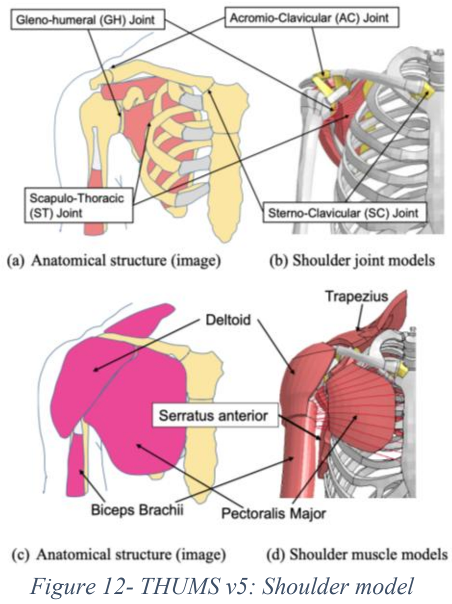


Figure 12- THUMS v5: Shoulder model
THUMS AM50 V5.3 Documentation (PDF). TOYOTA MOTOR CORPORATION and TOYOTA CENTRAL R&D LABS., INC

4.4.2.4. Muscle-Tendon Complex Model

The passive and active properties of muscles are simulated using a Hill-type muscle model with truss elements. The initial muscle length l_0 at t=0 is automatically derived from the initial geometry of the muscle elements. In LS-DYNA, the force, relative length, and shortening velocity of the muscle elements are expressed in terms of stress, strain, and strain rate, respectively. The stress of a muscle element is represented as the sum of the stresses from the contractile, passive, and damping components.

The strain ε is defined as: $\varepsilon = l/l_{orig} - 1$ = SNO x $l/l_0 - 1$, where l is the current muscle length; l_{orig} is the original muscle length and SNO is the initial stress ratio l_0/l_{orig}. At the distal end of the muscles, tendons are modeled using shell elements, with contact points between the shell elements and joint cartilage defined as shown in *Figure 13* [7] [8].

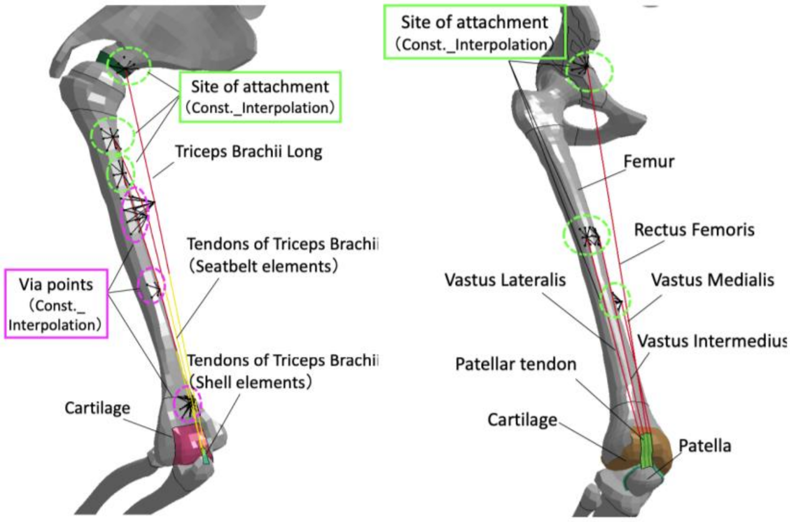


Figure 13 - Modeling of Tendons at the Distal Part of the Muscle Models
THUMS AM50 V5.3 Documentation (PDF). TOYOTA MOTOR CORPORATION and TOYOTA CENTRAL R&D LABS., INC

The muscle-tendon complex (*Figure 14)* is modeled by combining muscle truss elements and seatbelt elements in series. Via points, which denote the corners of muscle paths, are included. Due to seatbelt slip ring limitations, the elements must be arranged to avoid errors caused by free ends. The muscle-tendon complex is connected to the bones at both ends using *CONSTRAINED_INTERPOLATION [7] [8].

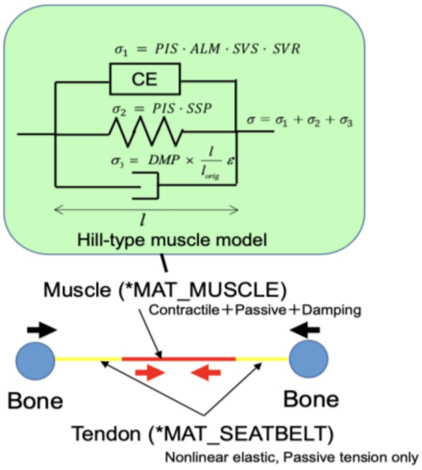


Figure 14 – Muscle-Tendon Complex of 1D Element
THUMS AM50 V5.3 Documentation (PDF). TOYOTA MOTOR CORPORATION and TOYOTA CENTRAL R&D LABS., INC.

Five distinct arrangements for muscle chains (refer to *Figure 15*) were identified:

1. *Type 1* models the muscle as a single element, suitable for short, straight muscles (e.g., adductor muscles of the lower limbs).
2. *Type 2* has a straight shape with a seatbelt-like element, ideal for straight muscles with long tendons (e.g., the brachialis muscle).
3. *Type 3* represents a curved muscle model with a single via point and two muscle elements, suitable for curved muscles without long tendons (e.g., the deltoid muscle).
4. *Type 4* describes curved muscle paths with a single via point, two muscle elements, and a seatbelt slip ring, typically used for multi-articular muscles (e.g., the triceps brachii muscle).
5. **Type 5** includes multiple slip ring via points, suitable for muscles with long tendons extending from the forearm or lower leg to the hands or feet (e.g., the extensor digitorum and extensor carpi ulnaris muscles) [7][8].

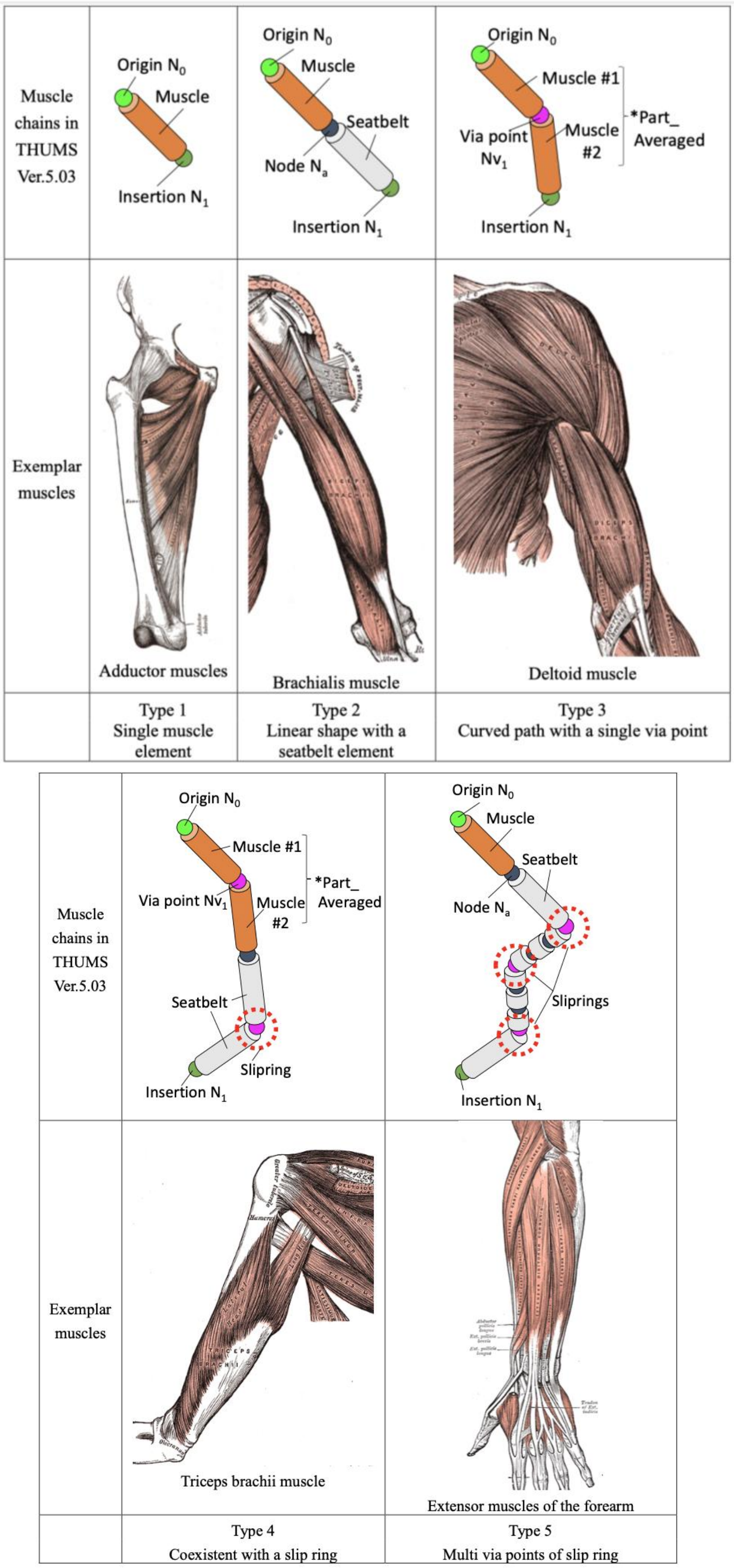


Figure 15- Types of Arrangements for Muscle Chains in THUMS v5
THUMS AM50 V5.3 Documentation (PDF). TOYOTA MOTOR CORPORATION and TOYOTA CENTRAL R&D LABS., INC.

4.4.2.5. Muscle Controller

The THUMS muscle controller operates alongside finite element (FE) analysis, determining Activation Levels of Muscles (ALM) based on displacement and force at each time step. Muscle components, modeled with Hill-type properties, generate contractive forces according to ALM. The controller includes two closed-loop feedback systems: one for posture control and one for force control [7][8].

- The *posture control system* detects changes in occupant posture during impacts or braking decelerations by monitoring joint angle variations. Its goal is to maintain the initial posture, predicting occupant kinematics and accounting for muscle tone conditions.
- The *force control system* replicates the forces exerted by braced drivers to support their body. The muscle state for a relaxed driver is controlled using only the posture system, while the braced driver uses both posture and force control.

The muscle control system is shown in *Figure 16*.

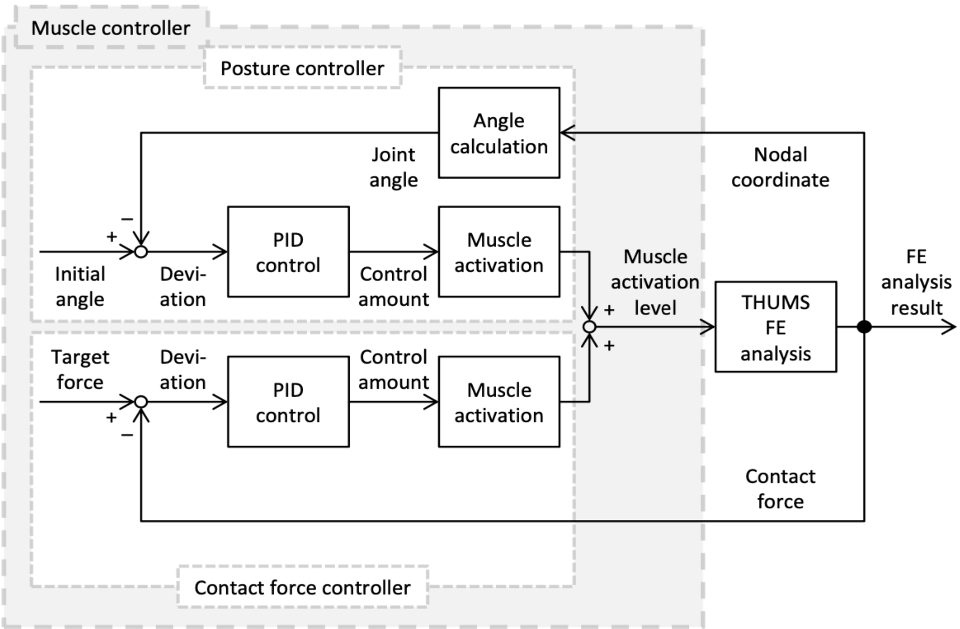


Figure 16 - Outline of muscle controller system
THUMS AM50 V5.3 Documentation (PDF). TOYOTA MOTOR CORPORATION and TOYOTA CENTRAL R&D LABS., INC.

4.4.2.6. Joint Angle Calculation

The body is divided into 17 parts, and 16 joints between these parts are monitored to evaluate angle changes. Joint angles are determined by selecting three nodes per body part: Node 1 represents the center, Node 2 the upper region, and Node 3 the front region. This configuration ensures alignment with the anatomical position, where the body stands erect, facing anteriorly, with arms at the sides, palms forward, and feet pointing forward [7][8].

4.4.3. Integration into Whole Body Model

The overall number of elements of THUMS Version 5 is about 280,000 approximately, corresponding to one-eighth of that of the previous version 4.
The whole-body model contains the FEM attributes listed in *Table 5.*

Version	Elements	Node	Part	Time Step [s]
5 AM50	285 792	185 897	416	5.4E-7

Table 5 - FEM Data Version 5

The complete body model includes a total of 256 skeletal muscles distributed throughout the body. These are categorized into 23 neck muscles, 42 arm muscles, 11 trunk muscles, and 52 leg muscles on each side. The muscle model comprises 808 parts of 1D muscle elements and 80 parts of seatbelt elements. The overall number of elements is 2,660 (1,726 beams, 888 seatbelts, and 46 shells). The entire muscle model weighs approximately 0.9 kg and is shown in *Figure 17* [7].

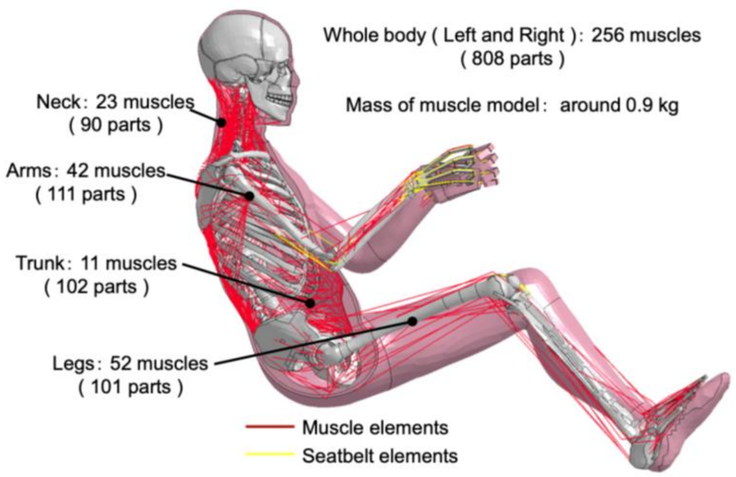


Figure 17 - THUMS v5: Whole Body Muscles
THUMS AM50 V5.3 Documentation (PDF). TOYOTA MOTOR CORPORATION and TOYOTA CENTRAL R&D LABS., INC.

4.4.4. Material Properties

Cortical bone and spongy bone were treated as isotropic elasto-plastic materials. Ligaments and tendons were characterized by either non-linear or linear elastic material properties, depending on experimental data sourced from the literature. The brain was modeled with linear visco-elastic material properties. Solid organs such as the liver, kidney, spleen, and pancreas were represented using a rubber-like material, while the lung utilized a padded material. To simulate impact responses, the heart and bowel were also modeled with the rubber-like material. Additionally, hollow organs like the stomach, aorta, vena cava, trachea, and esophagus were filled with tetrahedral elements containing a fluid-like elastic material. Muscles or flesh were likewise assumed to possess rubber-like material properties, while the skin was represented using either non-linear or linear elastic material properties [7].

The main materials used in LS-DYNA model are listed in *Table 6*.

<table>
<tr><th>Model Component</th><th>Material Type</th><th>LS-DYNA Material</th></tr>
<tr><td rowspan="2">Bone Model</td><td>Cortical Bone</td><td>MAT_24: MAT_PIECEWISE_LINEAR_PLASTICITY</td></tr>
<tr><td>Spongeous Bone</td><td>MAT_105: MAT_DAMAGE_2</td></tr>
<tr><td rowspan="4">Muscles and Ligaments</td><td rowspan="2">Muscles</td><td>MAT_62: MAT_VISCOUS_FOAM</td></tr>
<tr><td>MAT_B1: MAT_SEATBELT</td></tr>
<tr><td rowspan="2">Ligaments</td><td>MAT_181: MAT_SIMPLIFIED_RUBBER</td></tr>
<tr><td>MAT_34: MAT_FABRIC</td></tr>
<tr><td>Knee Ligaments</td><td>Knee Ligaments</td><td>MAT_19:MAT_STRAIN_RATE_DEPENDENT_PLASTICITY</td></tr>
<tr><td rowspan="3">Head Model</td><td>Skull</td><td>MAT_24: MAT_PIECEWISE_LINEAR_PLASTICITY</td></tr>
<tr><td>Brain</td><td>MAT_61: MAT_KELVIN-MAXWELL_VISCOELASTIC</td></tr>
<tr><td>CSF</td><td>MAT_1: MAT_ELASTIC_FLUID</td></tr>
<tr><td rowspan="3">Spine Model</td><td>Nucleus</td><td>MAT_76: MAT_GENERAL_VISCOELASTIC</td></tr>
<tr><td>Anulus</td><td>MAT_71: MAT_CABLE_DISCRETE_BEAM</td></tr>
<tr><td>Vertebrae</td><td>MAT_24: MAT_PIECEWISE_LINEAR_PLASTICITY</td></tr>
<tr><td rowspan="4">Organs Model</td><td>Solid Organs</td><td>MAT_181: MAT_SIMPLIFIED_RUBBER</td></tr>
<tr><td rowspan="2">Hollow Organs</td><td>MAT_34: MAT_FABRIC</td></tr>
<tr><td>MAT_1: MAT_ELASTIC_FLUID</td></tr>
<tr><td>Lungs</td><td>MAT_57: MAT_LOW_DENSITY_FOAM</td></tr>
</table>

Table 6 - THUMS v5: LS-DYNA Materials

4.5. THUMS Version 6

Version 6 was developed by integrating the comprehensive muscle data from Version 5 into Version 4. THUMS Version 6 has both a detailed human-body structure and activable muscles.

4.5.1. Acquisition of medical imaging data

The same database from Version 4 was used for Version 6.
A dataset from a 39-year-old male (173 cm, 77.3 kg, BMI 25.8) was selected for the AM50 model. The torso was scanned, while the head and extremities were based on Version 3 but refined for a finer mesh.
The muscle geometry, as for version 5, was derived from anatomical texts [8].

4.5.2. Anatomical Structures Description

The main anatomical features remain consistent with Version 4 *(see Paragraph 5.3.2.)*.
The following updates and improvements have been made:

- The element discretization has been optimized to ensure greater stability in calculations, and the mesh resolution for internal organs and soft tissues has been increased, improving the simulation of mechanical interactions.
- The pelvis geometry has been updated to better represent an average AM50.
- The cortical bone thickness for ribs and vertebrae has been modified to align with reference data.
- The abdominal tissue thickness has been updated to improve body representation [8].

The muscle and tendon models were taken from Version 5 *(refer to paragraph 5.4.2.1.)*.

4.5.3. Integration into Whole Body Model

The whole-body model contains the FEM attributes listed in *Table 7*.

Version	Elements	Node	Part	Time Step [s]
6 AM50	1 925 520	766 459	2 213	4.0E-7

Table 7 - FEM Data Version 6

The AM50 Version 6 model includes 262 skeletal muscles, with the muscle model consisting of 808 muscle parts and 80 seatbelt parts. The total number of elements is 3,336 (1,224 beams, 2,066 seatbelts, and 46 shells), and the muscle model weighs around 0.97 kg. The distribution of muscles across the body is illustrated in *Figure 18* [8].

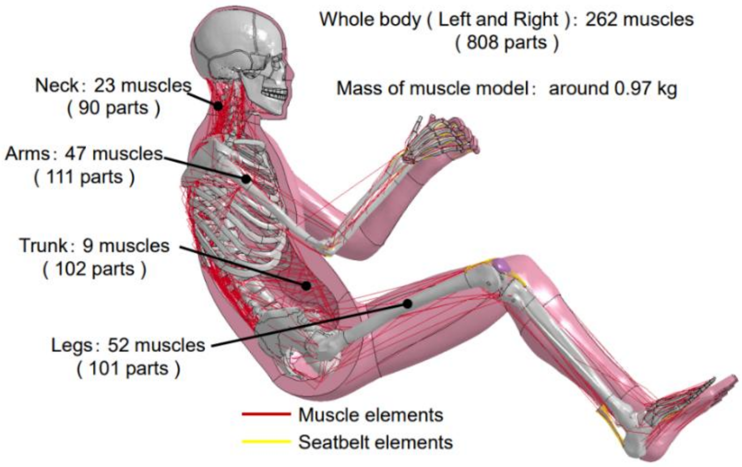


Figure 18 - THUMS v6: Whole Body Muscles
THUMS AM50 V6.1 Documentation (PDF). TOYOTA MOTOR CORPORATION and TOYOTA CENTRAL R&D LABS., INC.

4.5.4. Material Properties

The main materials used in LS-DYNA model are listed in *Table 8*.

Component	Material Type	LS-DYNA Material
Bone Model	Cortical Bone	MAT_24: MAT_PIECEWISE_LINEAR_PLASTICITY
	Spongeous Bone	MAT_105: MAT_DAMAGE_2
Muscles and Ligaments	Muscles	MAT_156: MAT_MUSCLE
	Tendons	MAT_B01: MAT_SEATBELT
	Ligaments	MAT_181: MAT_SIMPLIFIED_RUBBER
Head Model	Skull	MAT_24: MAT_PIECEWISE_LINEAR_PLASTICITY
	Brain	MAT_61: MAT_KELVIN-MAXWELL_VISCOELASTIC
	CSF	MAT_1: MAT_ELASTIC_FLUID
Spine Model	Nucleus	MAT_76: MAT_GENERAL_VISCOELASTIC
	Anulus	MAT_71: MAT_CABLE_DISCRETE_BEAM
	Vertebrae	MAT_24: MAT_PIECEWISE_LINEAR_PLASTICITY
Organs	Solid Organs	MAT_181: MAT_SIMPLIFIED_RUBBER
	Hollow Organs	MAT_34: MAT_FABRIC
	Lungs	MAT_57: MAT_LOW_DENSITY_FOAM
	Heart	MAT_181: MAT_SIMPLIFIED_RUBBER
Soft Tissues	Skin, Fat, Flesh	MAT_181: MAT_SIMPLIFIED_RUBBER

Table 8 - THUMS v5: LS-DYNA Materials

5. Methods and Tools

The primary focus of this study is the analysis of simulations conducted using the Finite Element Method (FEM), a numerical approach that enables the evaluation of complex biomechanical behaviors under various loading conditions. This method is particularly suited for studying the response of human body models to external forces, such as those experienced in impact scenarios. By discretizing the human body into smaller elements, FEM allows for a detailed investigation of stress distribution, deformation, and potential injury risks. To conduct these simulations, LS-DYNA, a highly advanced finite element solver, has been employed. The preprocessing and postprocessing phases were carried out using LS-PrePost, a dedicated tool from LST LLC that facilitates model preparation, mesh generation, boundary condition application, and results visualization.
The simulations were executed on HPC@POLITO, a project of Academic Computing within the Department of Control and Computer Engineering at the Politecnico di Torino. Additionally, post-analysis was refined using the THUMS® Injury Risk Visualization tool (IRV), whose functionality is detailed in the following paragraph.

5.1. THUMS® Injury Risk Visualization tool (IRV)

The THUMS® Injury Risk Visualization (IRV) is a tool provided by Toyota, whose primary purpose is the evaluation of the injury risk of bones and internal organs by processing the data generated from simulations [10].
The tool consists of two programs combined: a Command Line Interface (CLI) program and a web application.
Outlined below is a typical workflow, as illustrated in *Figure 20*:

I. *Data Extraction*

The IRV tool extracts data from the files produced by finite element analysis software. These files contain detailed information about the mechanical response of the THUMS model, including stress, strain, and displacement data for all body parts.

II. *CLI for .csv File Generation*

The Command-Line Interface (CLI) is used to process the simulation results and extract the necessary information in a .csv format in order to use it in the THUMS IRV web application.

The .csv file is typically organized into rows and columns that represent:

- Node IDs, Element IDs.
- Mechanical parameters (strain, stress, etc.).
- Injury metrics and thresholds.

III. Visualization on Web Application

The web application generates a color-coded visualization of injury risks directly on the THUMS model *(see figure 19).* Different colors represent different levels of injury severity, making it easy to identify high-risk areas [10].

- Blue: Low risk or minimal strain/stress (0-20%).
- Green: Moderate risk, indicating potential for minor injury (20-40%).
- Yellow: Increased risk, approaching injury thresholds (40-60%).
- Orange: High risk, where significant injuries are likely (60-80%).
- Red: Critical risk, indicating areas of severe injury or failure (80-100%).

Bones and internal organs are shown separately, allowing for a detailed analysis of each structure. The following bones and organs are analyzed: skull, face, cervical spine, thoracic spine, lumbar spine, ribs, sternum, clavicle, scapula, humerus, forearm bones, pelvis, femur and lower leg bones; brain, heart, lungs, aorta, liver, kidneys, spleen, stomach, intestines and knee ligaments.

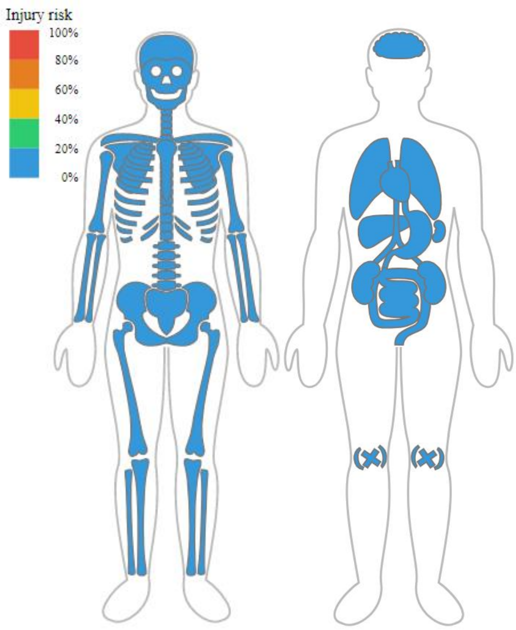


Figure 19 - IRV web application output: color map

Moreover, the THUMS IRV model allows for customization of age and gender to accurately represent different demographic groups by adjusting the reference values and thresholds applied in injury calculations.
In this study, a standard age of 35 years was applied to a male model.

IV. Injury Criteria Analysis

The IRV tool uses established injury criteria to quantify the risk of injuries:

- Maximum Principal Strain (MPS): it measures the maximum deformation along the principal direction in a material under stress. It is a scalar value representing the greatest elongation or compression an element experiences instantaneously.
- Cumulative Strain Damage Measure (CSDM): it quantifies the percentage of a material's volume that exceeds a predefined strain threshold. It evaluates cumulative strain across a region or organ and is particularly useful for predicting widespread damage.
- Injury Risk Curves (IR): Provides probabilistic estimates of injury occurrence based on biomechanical thresholds [10].

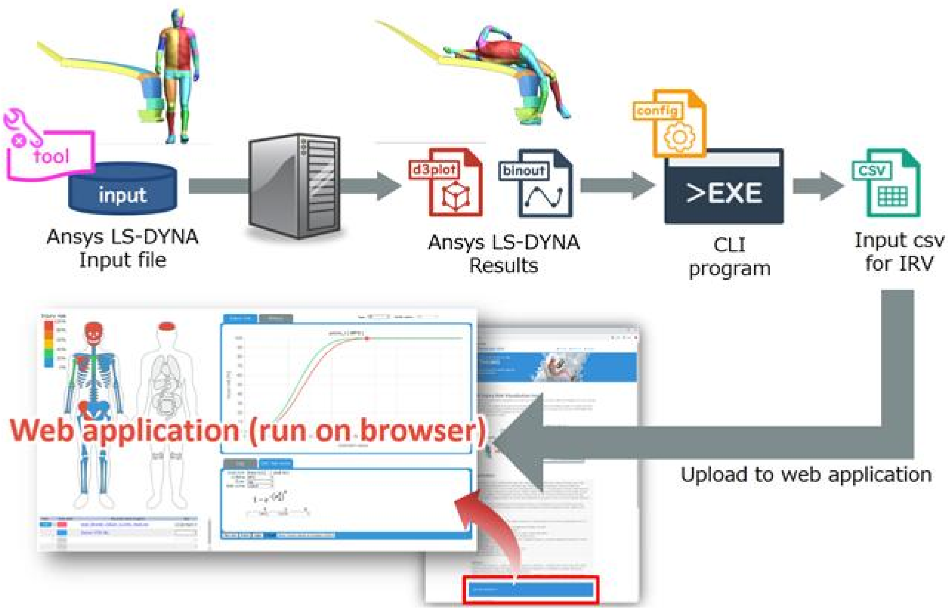


Figure 20 - THUMS IRV tool workflow
JSOL Corporation JMAG-Designer Ver.22.1 Release. 21 Oct. 2022, https://www.jsol-cae.com/en/news/2022/release/1021a.html.

6. Simulation Scenarios

The objective of this chapter is to describe in detail the three simulated scenarios, outlining the characteristics and the methodologies employed.
The key parameters for each scenario are summarized in *Table 9.*

	Impact Type	Velocity	Velocity Type	Duration
#1	Frontal Sled	14 m/s	Transitional	0.2 s
#2	Fall from sitting	2.2 m/s	Transitional	0.5 s
#3	Fall from standing	7 rad/s + 3 m/s	Rotational + Transitional	0.4 s

Table 9 - Simulation Scenarios Overview

7.1. Simulation Cards: Common Features Across All Scenarios

To ensure the stability and accuracy of the simulations, the following control cards were applied to each scenario: *CONTROL_ACCURACY, *CONTROL_BULK_VISCOSITY, *CONTROL_CONTACT, *CONTROL_DYNAMIC_RELAXATION, *CONTROL_ENERGY, *CONTROL_HOURGLASS, *CONTROL_MPP_DECOMPOSITION_TRANSFORMATION, *CONTROL_MPP_IO_LSTC_REDUCE, *CONTROL_MPP_IO_NOFULL, *CONTROL_OUTPUT, *CONTROL_SHELL, *CONTROL_SOLID, *CONTROL_SOLUTION, *CONTROL_TERMINATION.
For post-processing and result analysis in LS-Prepost and IRV, the following database cards were implemented: *DATABASE_BINARY_D3PLOT, *DATABASE_CURVOUT, *DATABASE_EXTENT_BINARY, *DATABASE_GLSTAT, *DATABASE_HISTORY_NODE, *DATABASE_NODOUT, *DATABASE_RCFORC.
Additionally, gravity effects were incorporated using the *LOAD_BODY_Z function with a predefined curve, whose parameters are detailed in *Table 10*.

x(s)	0.000	0.002	0.004	0.006	0.008	0.010	0.012	0.014	0.016	0.018	0.020	10.000
y(mm/s²)	0	482	1072	1876	3325	4903	6368	7701	8738	9328	9807	9807

Table 10 - L_doby_Z Curve Parameters

7.2. First scenario: Frontal Sled

In the first simulation, the THUMS model was subjected to a frontal sled test at a velocity of 50 km/h. The setup included the THUMS model seated in a simplified rigid seat, equipped with a 3-point seatbelt (respectively, *Figure 21* and *Figure 22*). The goal was to evaluate the injury risks to bones and internal organs during a frontal collision. A transitional velocity was applied to the seat and pedals in x direction.
The whole model was subjected to gravity, and the rigid seat was constrained in z translational and rotational directions. Contact definitions (*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_ID) were established between THUMS and the seat, as well as between THUMS and the seatbelt.
The setup and simulation at the end time are shown in *Figure 23* and *Figure 24*.
Thums versions tested in this scenario are reported in *Table 11*.

	Version 4	Version 5	Version 5 w/ Muscles Activation	Version 6	Version 5 w/ Muscles Activation
Frontal Sled	Y	Y	Y	Y	Y

Table 11 - THUMS Versions Tested in First Scenario

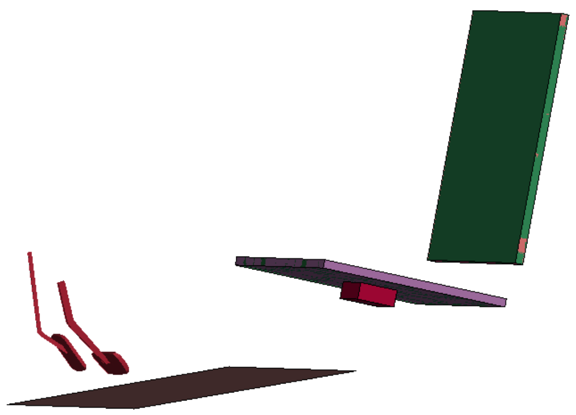


Figure 13 - Rigid Seat, floor, pedals

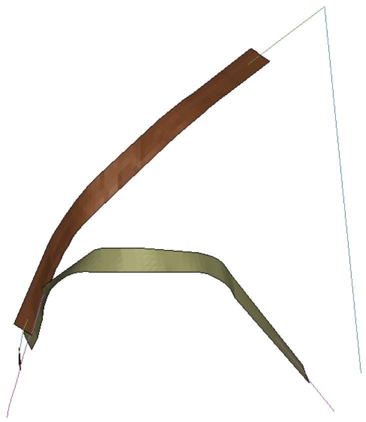


Figure 22 - 3-points seatbelt

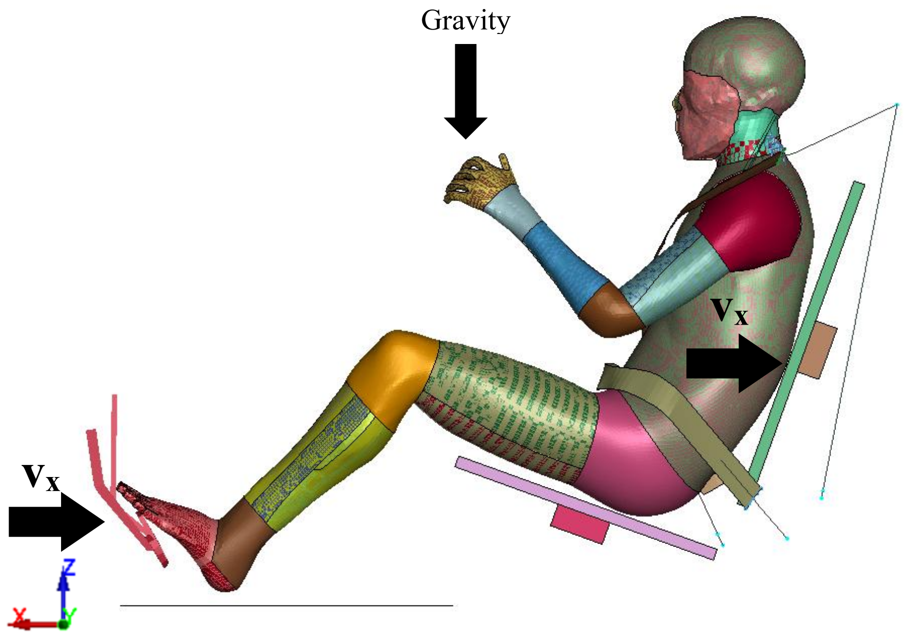


Figure 23 - 1st Simulation Setup

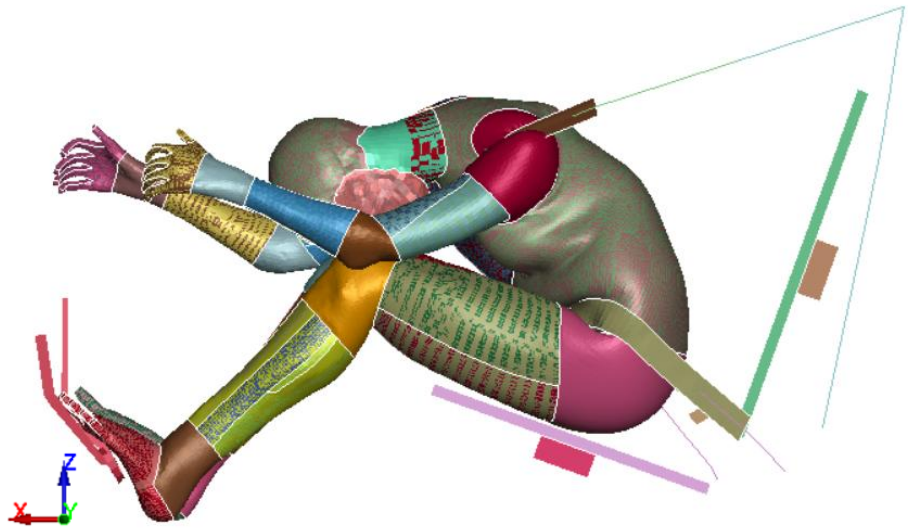


*Figure 24 - Simulation at t=endtime**

**refer to next paragraph*

7.2.1. Simulation cards: First Scenario

*CONTROL_TERMINATION $# endtime: 0.2

*CONSTRAINED_RIGID_BODIES

*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_ID

*INITIAL_VELOCITY_GENERATION

$#nsid/pid	styp	omega	vx	vy	vz	ivatn	icid
Seat&Pedals	1	0.0	-14000.0	0.0	0.0	0	0

Parameters for postural control are taken from Toyota's validation set [3] and are set as in *Table 12*.

Region	Total Muscles	Controllable	Uncontrollable	Activation Ratio
Neck	23	23	0	0.800
Trunk	9	7	2	0.800 (C_ABD01 - C_ABD07), 0.000 (C_ABD08 - C_ABD09)
Lower Extremity	52	39	13	0.800 (C_LEX01 - C_LEX39), 0.000 (C_LEX40 - C_LEX52)
Upper Extremity	47	38	9	0.800 (C_UEX01 - C_UEX38), 0.000 (C_UEX39 - C_UEX47)

Table 12 - Activation Ratio of Each Muscle

7.3. Second scenario: Fall from seated

The second simulation analyzed the effects of a lateral fall from a seated position at a velocity of 2200 mm/s → 7.92 km/h. For the setup, the same rigid seat from the first scenario was used, with a lateral velocity applied to the THUMS body to simulate the fall to the ground.

The whole model was subjected to gravity, and the rigid seat was constrained in all translational and rotational directions (x, y, z). Contact definitions (*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_ID) were established between THUMS and the seat, as well as between THUMS and the floor.

The setup and simulation at the end time are shown in *Figure 25* and *Figure 26*.

Thums versions tested in this scenario are reported in *Table 13*.

	Version 4	Version 5	Version 5 w/ Muscles Activation	Version 6	Version 5 w/ Muscles Activation
Fall from seated	Y	Y	Y	Y	Y

Table 13 - THUMS Versions Tested in Second Scenario

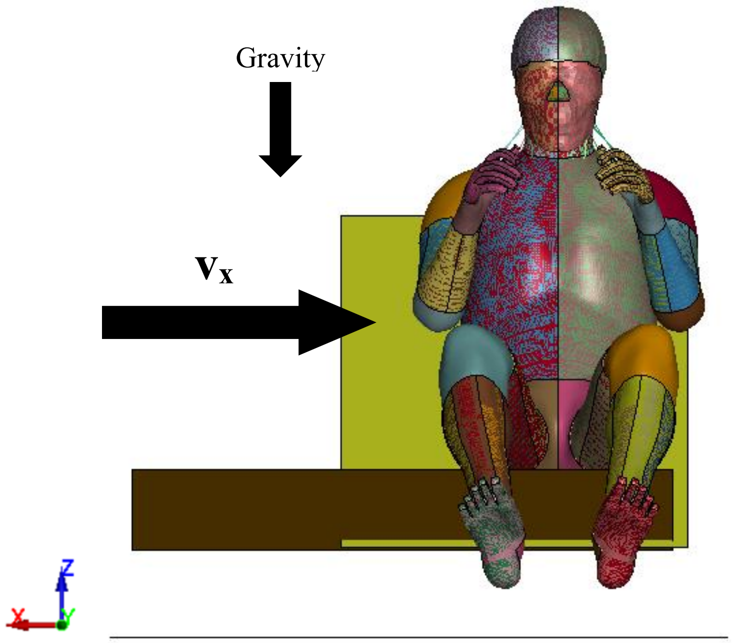


Figure 25 - 2nd Simulation Setup

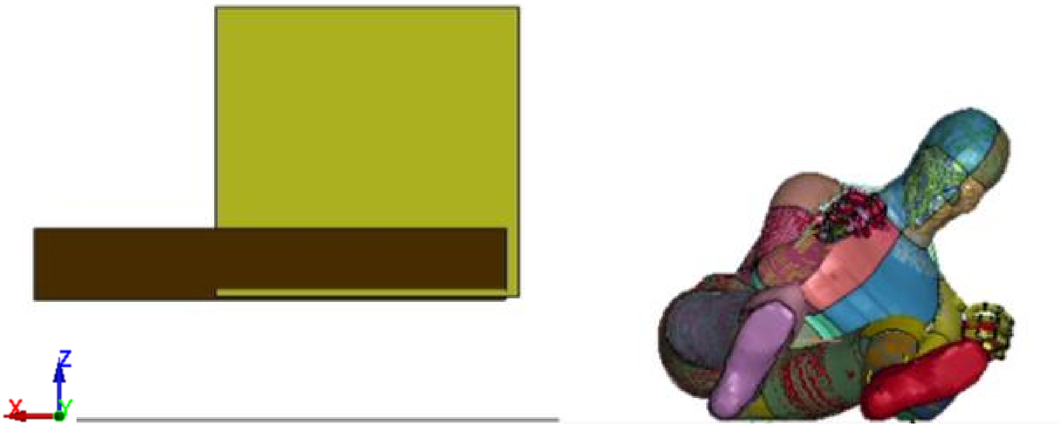


*Figure 14- Simulation at t=endtime**

**refer to next paragraph*

7.3.1. Simulation Cards: Second Scenario

*CONTROL_TERMINATION $# endtime 0.5

*CONTROL_TIMESTEP

*CONSTRAINED_RIGID_BODIES

*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_ID

*INITIAL_VELOCITY_GENERATION

$# nsid/pid	styp	omega	vx	vy	vz	ivatn	icid
4	1	0.0	-2200.0	0.0	0.0	0	0

Parameters for postural control are taken from Toyota's validation set [1] and are set as in *Table 14*.

Region	Total Muscles	Controllable	Uncontrollable	Activation Ratio
Neck	23	23	0	0.800
Trunk	9	7	2	0.800 (C_ABD01 - C_ABD07), 0.000 (C_ABD08 - C_ABD09)
Lower Extremity	52	39	13	0.800 (C_LEX01 - C_LEX39), 0.000 (C_LEX40 - C_LEX52)
Upper Extremity	47	38	9	0.800 (C_UEX01 - C_UEX38), 0.000 (C_UEX39 - C_UEX47)

Table 14 - Activation Ratio of Each Muscle

7.4. Third scenario: Fall from a standing position

The third simulation involved a fall to the ground from a standing position with an angular velocity of 7 rad/s and a transitional vertical velocity of 3000 mm/s.

The THUMS body was subjected to gravity

A contact (*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_ID) was established between THUMS and the floor.

This simulation aims to investigate the behavior of the manually repositioned versions, compared with the pedestrian Version 4 provided by Toyota, to move beyond the automotive application field.

The setup and simulation at the end time are shown in *Figure 27* and *Figure 28*.

Thums versions tested in this scenario are reported in *Table 15*.

	Version 4	Version 4 Manually Manipulated	Version 5	Version 6 Manually Manipulated
Fall from standing	Y	Y	N	Y

Table 15 - THUMS Versions Tested in Third Scenario

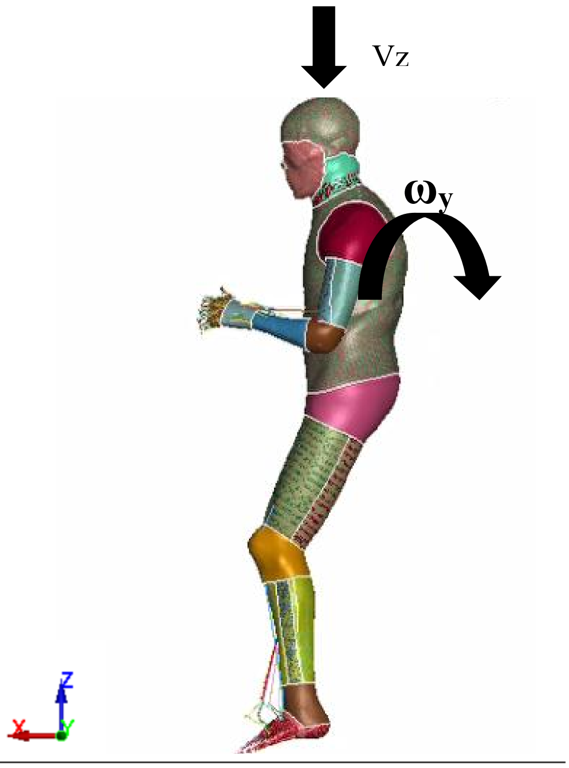


Figure 27 - 3rd Simulation Setup

*Figure 28 - Simulation at t=endtime**

**refer to next paragraph*

7.4.1. Simulation cards: Third Scenario

*CONTROL_TERMINATION $# endtime 0.4

*CONSTRAINED_RIGID_BODIES

*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_ID

*INITIAL_VELOCITY_GENERATION

$#	id	styp	omega	vx	vy	vz	ivatn	icid
	0	1	-7.0	0.0	0.0	-3000.0	0	0

$#	xc	yc	zc	nx	ny	nz	phase	irigid
	0.0	0.0	0.0	0.0	1.0	0.0	0	0

7.4.2. Pre- setting: THUMS repositioning

The THUMS model was repositioned from an occupant to a pedestrian posture. To achieve this (results in *Figure 30*), a velocity of 9000 mm/s was applied to the torso and 1000 mm/s to the lower limbs. The model was first laid down horizontally and then rotated into a vertical standing position. The repositioning procedure is resumed in *Figure 29*.

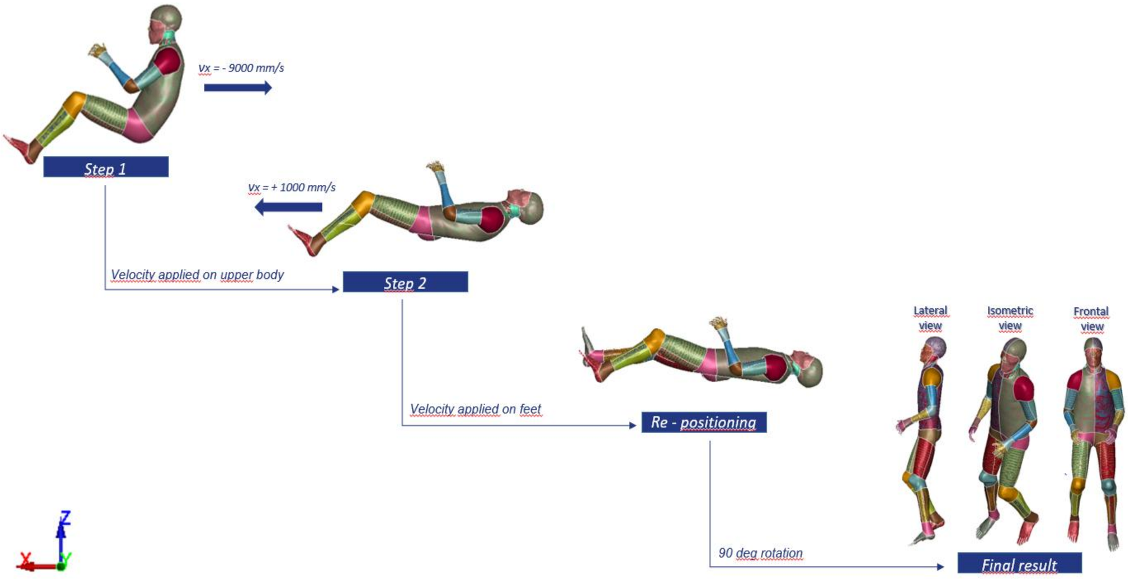


Figure 29 - THUMS Repositioning Procedure

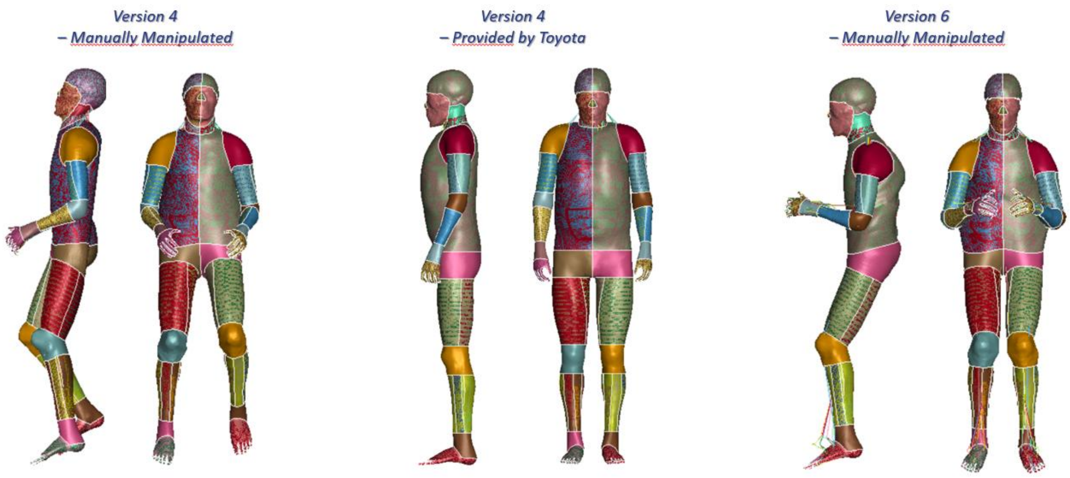


Figure 30 - THUMS Repositioning Results

Version 5 encountered issues during repositioning, as the desired position was not achieved (see *Figure 31*), and the internal structures of the THUMS body, in particular at the pelvis level, became deformed. This led to instability. Consequently, Version 5 was excluded from the third simulation.

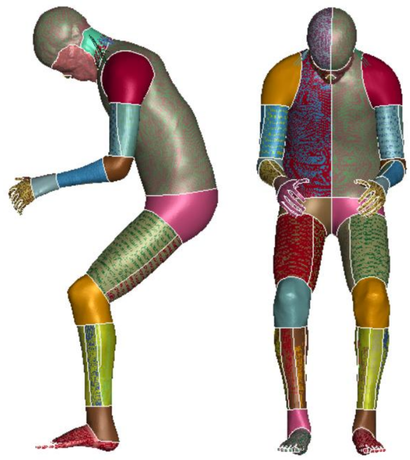


Figure 31 - THUMS Repositioning Results v5

7.4.3. Simulation cards: THUMS Repositioning

*CONTROL_TERMINATION $# endtime 0.2

*CONSTRAINED_RIGID_BODIES

*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_ID

*INITIAL_VELOCITY_GENERATION

1) $#	id	styp	omega	vx	vy	vz	ivatn	icid
	up_body	1	0.0	-9000.0	0.0	0.0	0	0
2) $#	id	styp	omega	vx	vy	vz	ivatn	icid
	feet	1	0.0	1000.0	0.0	0.0	0	0

7. Results

The Color Maps obtained from the IRV tool illustrate the spatial distribution of stress and strain within the body during the three test scenarios. These visual representations provide crucial insights into regions of high biomechanical stress, which correspond to potential injury sites. All resulting color maps are presented in *APPENDIX A*.
The injury risk assessment is based on biomechanical parameters such as Maximum Principal Strain (MPS), Cumulative Strain Damage Measure (CSDM), and Injury Risk

(IR). These parameters offer valuable insights into the likelihood and severity of injuries across various anatomical structures and are reported in detail in *APPENDIX B.*

7.1. First Scenario Results

This frontal sled simulation provides significant insights into the distribution of stresses and damages across different body regions. Overall, the chest area experiences the highest levels of stress, which aligns with the expected effect of the seatbelt. This is evidenced by the high peak values observed in the ribs, sternum, and clavicles, which are the regions most impacted by the restraint system. The extremities experience comparatively lower stresses, suggesting that are less involved in the crash dynamics. Internal organs, such as the lungs, liver, and kidneys, also sustain substantial damage during the crash.

When comparing the different simulation versions, some key patterns emerge: Version 5 consistently shows the highest bone damage, particularly in regions like the ribs and clavicles. Versions 4 and 6 instead display a more homogeneous distribution of bone injuries, but a greater damage to internal organs, especially in areas such as the liver and lungs. This suggests that while bone injuries might be more localized in these versions, the organs experience more widespread trauma.

Moreover, in this simulation it is evident the effect of including a muscular component. In Versions 5_MA and V6_MA, where muscle tissue is introduced, bone damage is generally reduced. However, this comes at the cost of increased organ damage, likely due to heightened muscular tension during the crash. The increased muscle contraction and the subsequent force transmission to internal organs contribute to the greater organ injury observed in these versions.

7.2. Second Scenario Results

In the second simulation, the results show significantly lower values compared to the previous crash test simulation. This is expected due to the low-impact nature and relatively low speed of the event. The damage to internal organs is almost zero, highlighting the lower forces involved in this type of fall.

The regions most affected in this scenario are the left pelvis (the primary point of impact with the ground). In Version 5, stresses are also elevated in the clavicles, spine, and rib cage, particularly in the thoracic and lumbar regions.
When comparing the versions, the injury risk parameters show similar patterns to the previous analysis. Versions 4 and 6 have lower bone damage but higher organ damage, indicating a more balanced injury distribution across the skeletal structure. However, Version 5 better replicates the behavior of internal organs. The trend between versions with and without muscle activation remains consistent with the previous scenario.

7.3. Third Scenario Results

In the third simulation, Version 5 could not be tested.
Versions 4 and 6, which were manually manipulated (MM), were compared with the officially released Version 4 by Toyota. The results from these versions are consistent with Toyota's model.
Since all versions share the same anatomical detail, it is not surprising that the results for these regions are similar across the different versions. Both Version 4 and Version 6 show comparable injury patterns, with small differences likely due to variations in the fall dynamics and how the body contacts the ground.
The most affected areas are the skull and pelvis, which are the primary points of contact with the ground. As in the previous simulations, the limbs are less impacted. The spine is also affected, and the extent of the damage depends more on the dynamics of the fall than on the version of the model used.

7.4. THUMS v4 vs. THUMS v5 vs. THUMS v6

By analyzing the differences between THUMS v4, v5, and v6, as well as configurations with and without muscle activation, key trends emerge in how forces are transmitted and absorbed by the human body.
Significant variations in injury risk can be observed across the three scenarios:

- *THUMS v4,* compared to the later version, shows a broader and uniform distribution of forces, with noticeable stress concentrations in the thoracic region, sternum, and clavicle. These areas experience higher stress accumulation, which is likely due to its less advanced soft tissue modeling.

- *THUMS v5* demonstrates more localized stress concentrations, particularly in the ribcage and shoulder regions. The clavicle and ribs exhibit higher peak stress values compared to v4, reflecting the model's enhanced structural differentiation and rigidity. It also shows a more pronounced injury risk to bones, especially in the upper body, with internal organs experiencing more consistent damage patterns.
- *THUMS v6* offers a more refined and realistic distribution of forces, with lower peak stresses in individual structures and a smoother transition of forces throughout the body. This version provides a more accurate representation of how forces are transmitted through bones, muscles, and soft tissues, resulting in a more accurate prediction of injuries.

7.5. Muscle Activation vs. No Muscle Activation

- Without muscle activation (No_MA), the force transmission appears more concentrated in specific bony structures, particularly the clavicle, sternum, and ribs. The lack of active muscle response leads to higher stress in these regions, making them more susceptible to fractures.
- With muscle activation (MA), stress distribution is spread across surrounding tissues. This results in a noticeable reduction in peak stress values in bones, but in an increase localized organ stress due to active muscle contraction. This suggests that muscle contraction helps absorb part of the impact energy, reducing direct loads on skeletal structures, but potentially increasing the risk of internal organ damage.

Overall, the results highlight the importance of including muscle activation in injury simulations, as it influences both skeletal and soft tissue injury risks in complex ways. While muscle activation reduces bone fractures, it may redirect forces to internal organs, emphasizing the need for an integrated approach when designing safety measures and evaluating occupant injury risks.

8. Conclusions

The comparison of THUMS v4, v5, and v6 highlights a significant increase in biofidelity across versions, with v6 offering the most realistic representation of human biomechanics. The enhanced anatomical detail in THUMS v4 and v6 improves the accuracy of force distribution predictions, particularly in complex scenarios. The ability to differentiate structures more precisely enables better injury risk assessments, guiding advancements in occupant safety measures.

Muscle activation proves to be a crucial factor in biomechanical modeling, as it redistributes impact forces, mitigating bone fractures but increasing localized stress on internal organs. This dual effect highlights the importance of integrating active muscle response into crash simulations to develop more comprehensive injury prevention strategies.

The first scenario results align with expectations, showing stress distributions consistent with predicted biomechanical responses. The second scenario exhibits lower injury values due to the low-speed impact nature of the test, where the reduced velocity leads to decreased force transmission and minimal structural damage.

The repositioning of the THUMS model is feasible; however, graphical analysis reveals visible errors in alignment. Despite these visual discrepancies, the resulting biomechanical responses remain consistent with the official model provided by Toyota, ensuring that the simulation outputs retain their validity. Differences observed in the third scenario stem not only from the model variations but also from modifications in the fall dynamics.

Overall, this study underscores the necessity of incorporating muscle activation, enhanced anatomical detail, and realistic impact dynamics into injury simulations for more accurate real-world injury predictions. The continued refinement of THUMS models is essential for improving vehicle safety and occupant protection.

9. APPENDIX A - Colour Maps

First Scenario

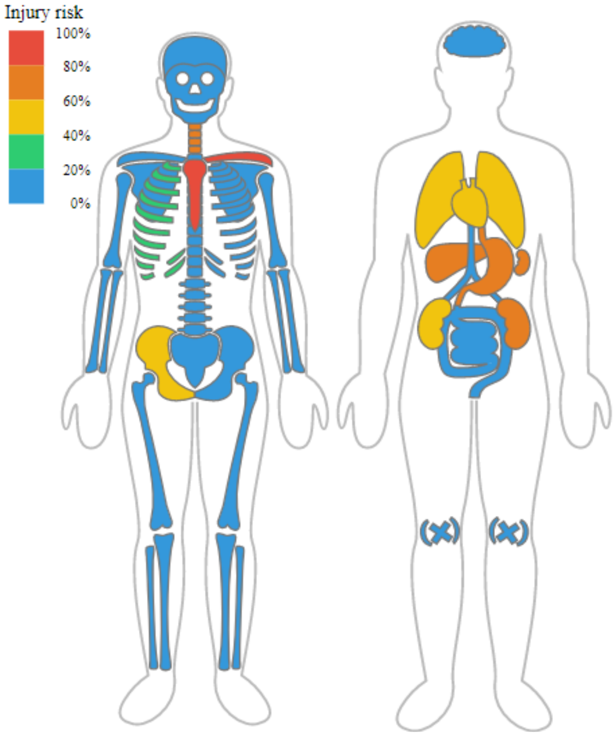


Figure 32 - IRV Color Map - THUMS v4 Frontal Sled

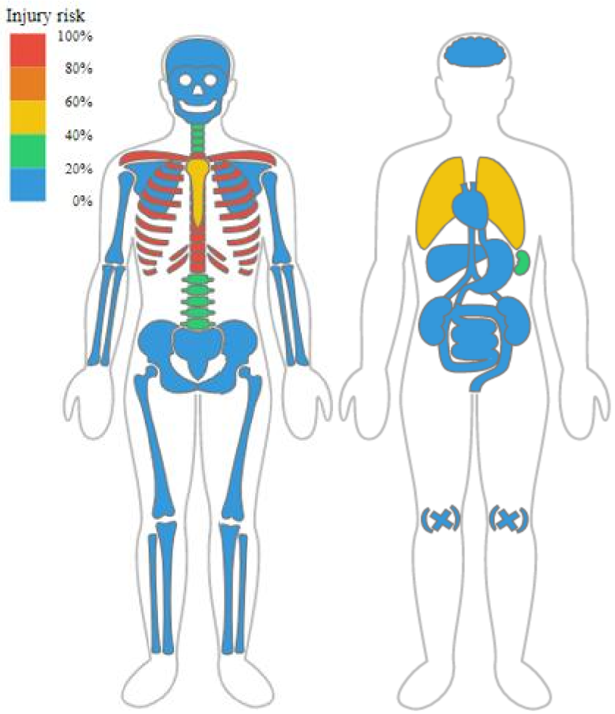


Figure 33 - IRV Color Map - THUMS v5 (w/out Muscle Activation) Frontal Sled

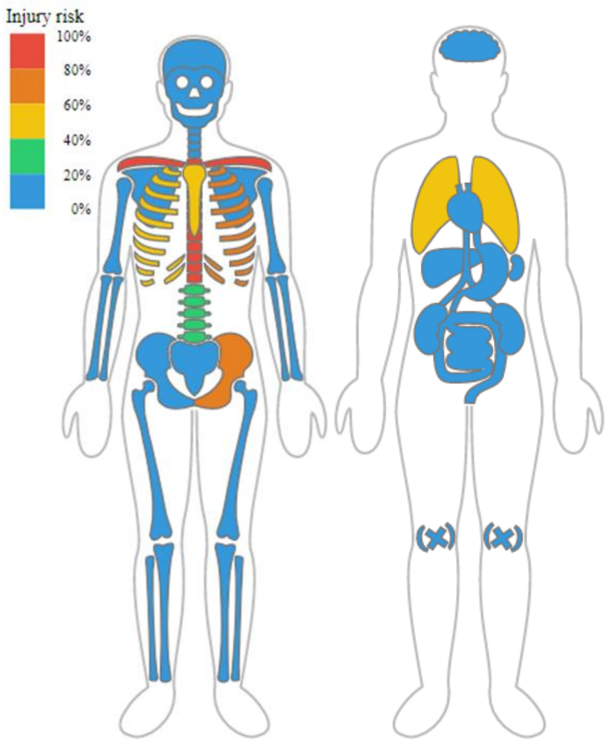


Figure 34 - IRV Color Map - THUMS v5 (w/ Muscle Activation) Frontal Sled

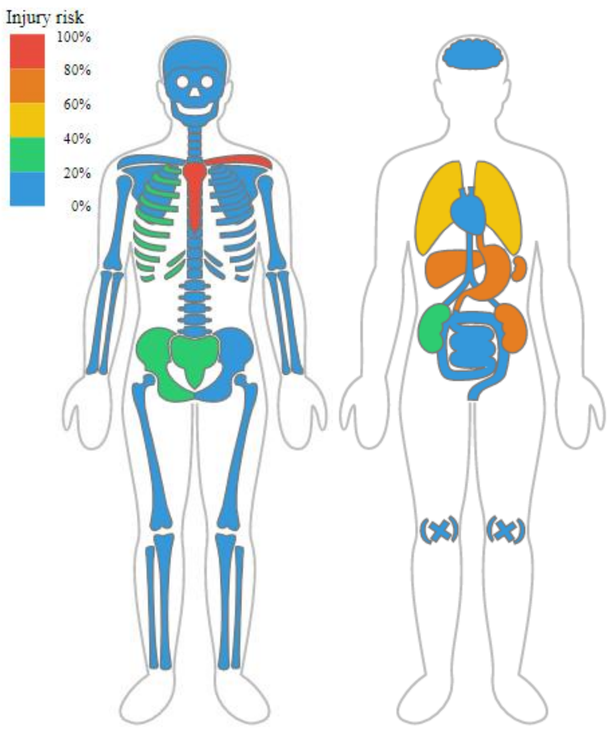


Figure 35 - IRV Color Map - THUMS v6 (w/out Muscle Activation) Frontal Sled

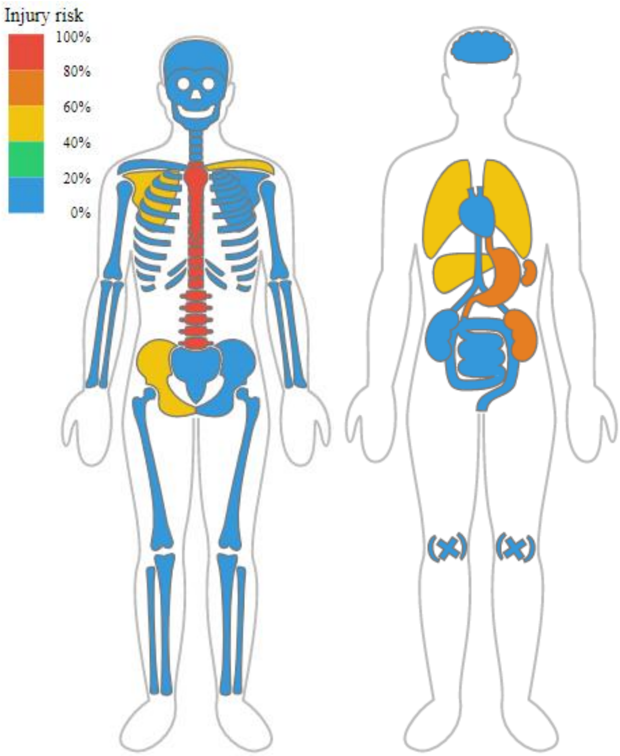


Figure 36 - IRV Color Map - THUMS v6 (w/ Muscle Activation) Frontal Sled

Second Scenario

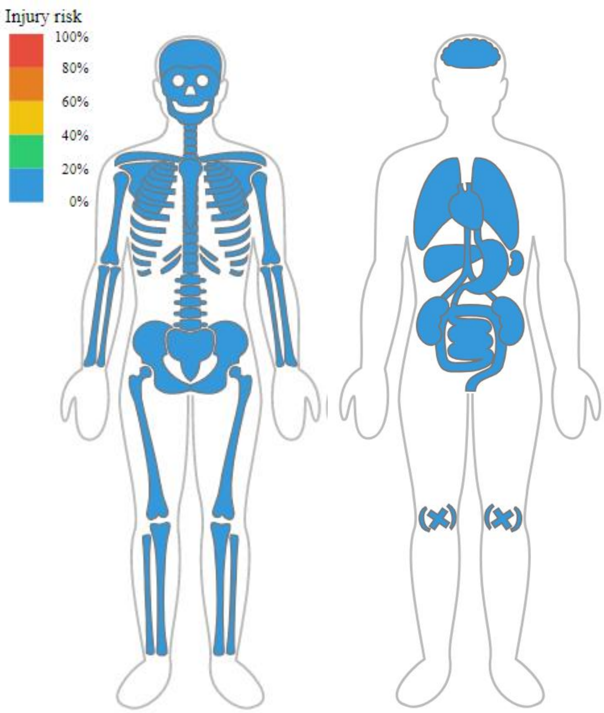


Figure 37 - IRV Color Map - THUMS v4 Fall from Seated

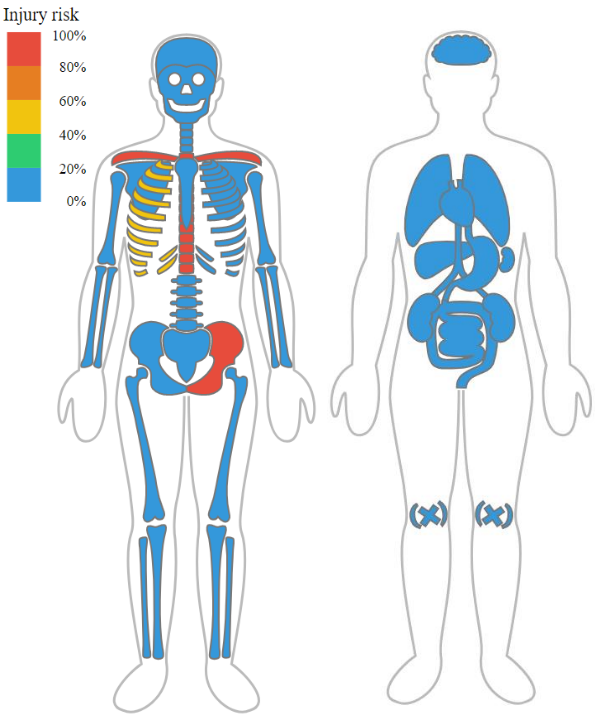


Figure 38 - IRV Color Map - THUMS v5 (w/out Muscle Activation) Fall from Seated

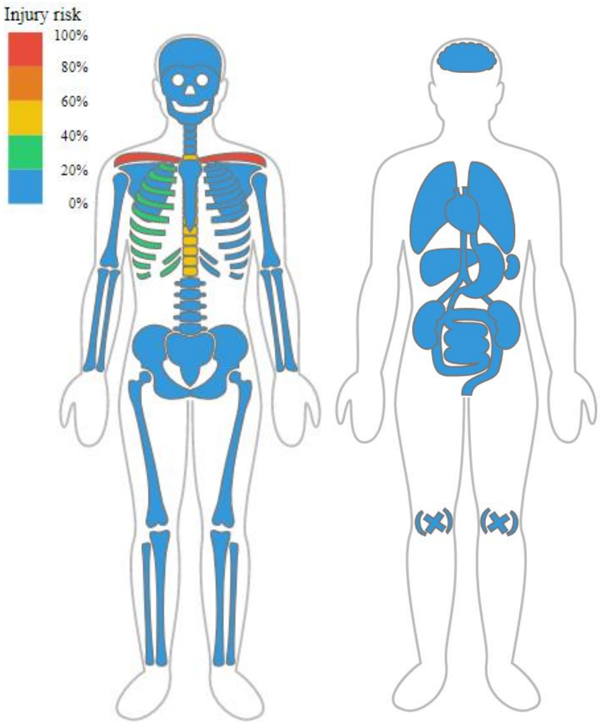


Figure 39 - IRV Color Map - THUMS v5 (w/ Muscle Activation) Fall from Seated

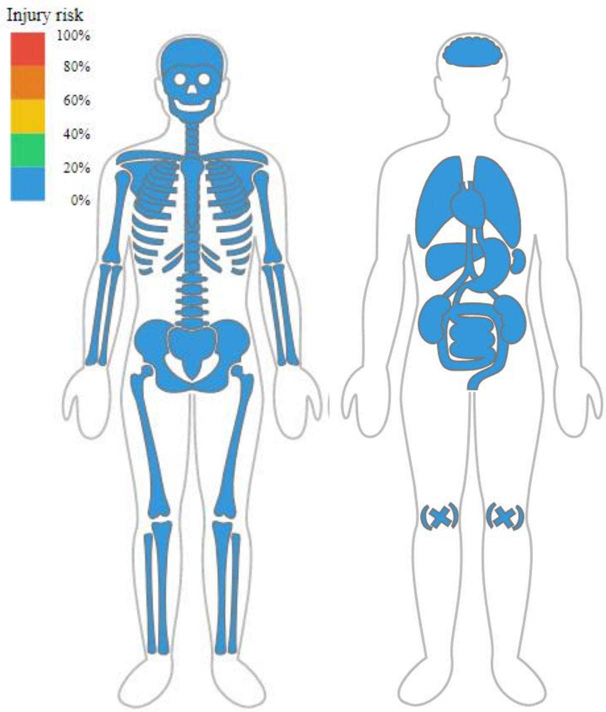


Figure 40 - IRV Color Map - THUMS v6 (w/out Muscle Activation) Fall from Seated

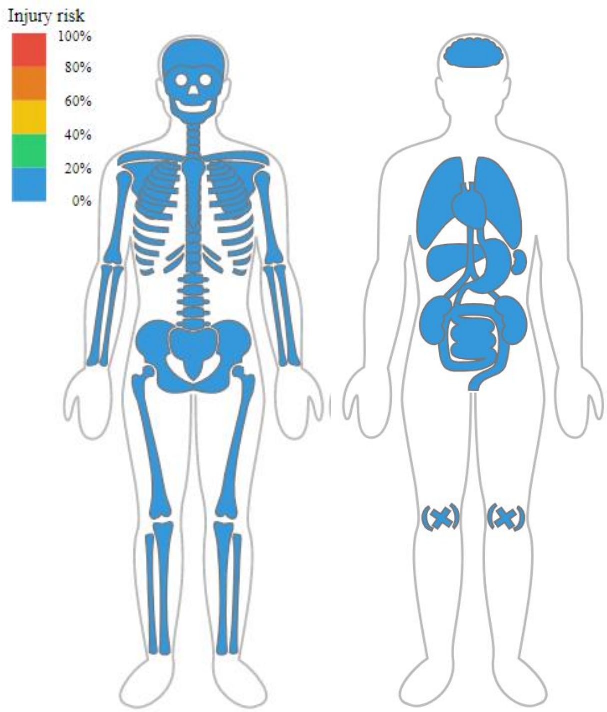


Figure 41 - IRV Color Map - THUMS v6 (w/ Muscle Activation) Fall from Seated

Third Scenario

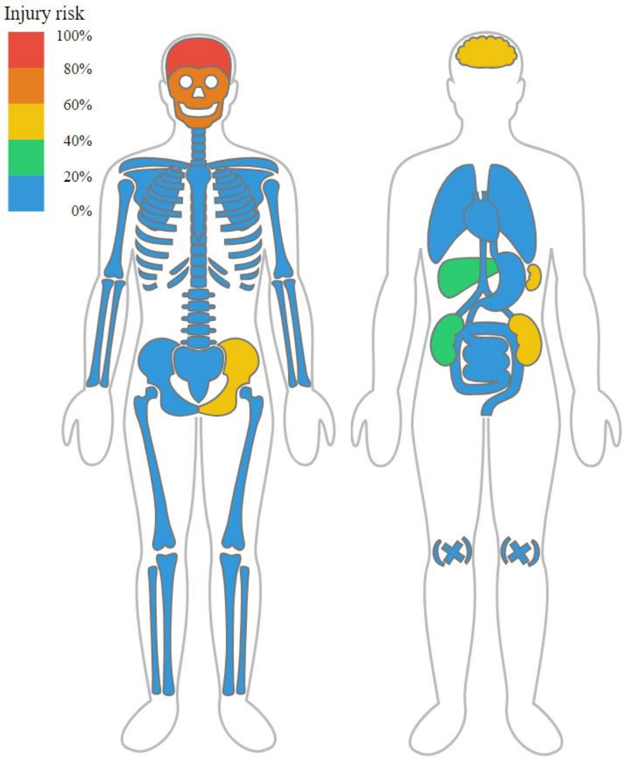


Figure 42 - IRV Color Map - THUMS v4 (Manually Manipulated) Fall from Standing

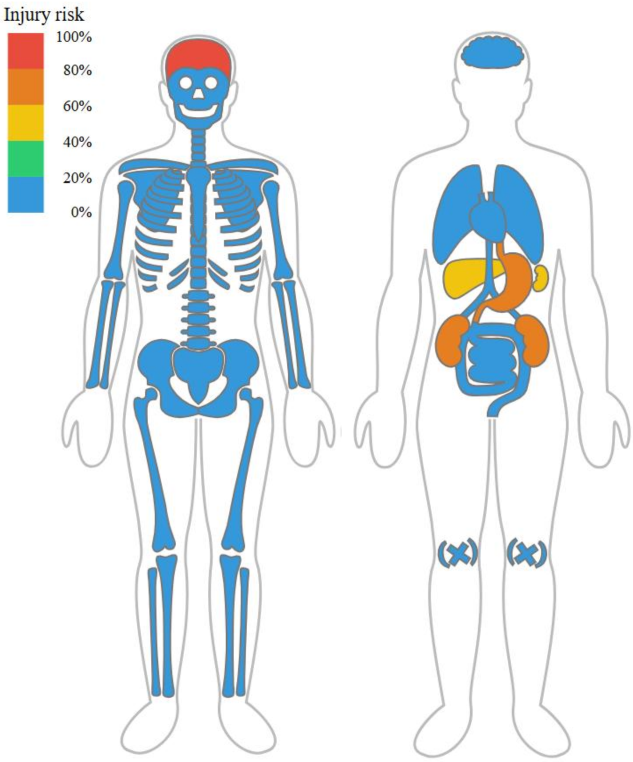


Figure 43 - IRV Color Map - THUMS v4 (Provided by Toyota) Fall from Standing

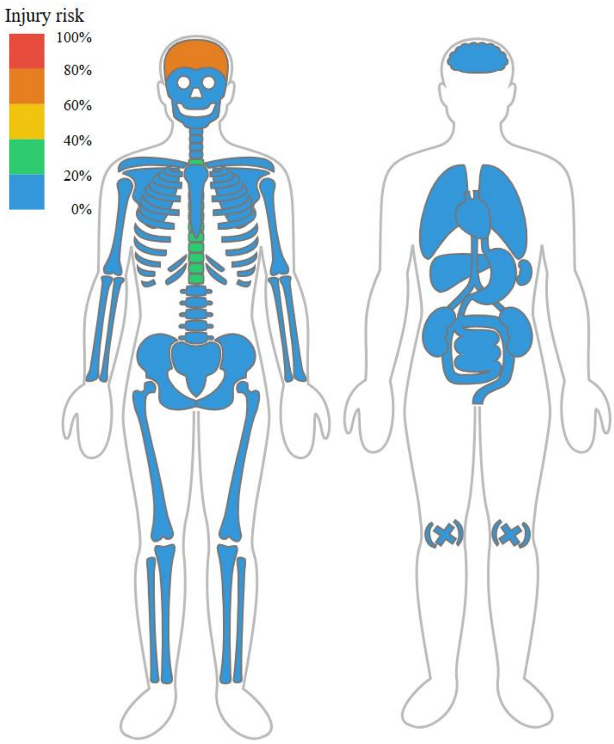


Figure 44 - IRV Color Map - THUMS v6 (Manually Manipulated) Fall from Standing

10. APPENDIX B - Injury Risk Parameters

First Scenario

BONES	MPS	Injury Risk
SKULL	0,004821	0,37%
FACE	0,00161	0%
CERVICAL SPINE	0,03422	74,63%
THORACIC SPINE	0,008028	1,72%
LUMBER SPINE	0,007595	1,46%
L - CLAVICLE	0,042155	92,36%
R - CLAVICLE	0,003255	0,11%
STERNUM	0,056222	99,78%
L - SCAPULA	0,015914	12,77%
L - RIB [MAX = 01]	0,009658	2,99%
R - RIB [MAX = 12]	0,022818	33,27%
R - SCAPULA	0,009373	2,73%
L - HOMERUS	0,014121	9,09%
R - HOMERUS	0,010937	4,32%
L - FOREARM	0,0029	0,08%
R-FOREARM	0,002838	0,08%
SACRUM	0,017923	17,75%
L - PELVIS	0,012876	6,96%
R - PELVIS	0,025778	44,25%
L - FEMUR	0,003154	0,10%
R - FEMUR	0,002949	0,09%
L - LOWER LEG	0,005311	0,50%
R - LOWER LEG	0,005	0,42%

Table 56 – Injury Risk Parameters, Bones – THUMS v4 Frontal Sled

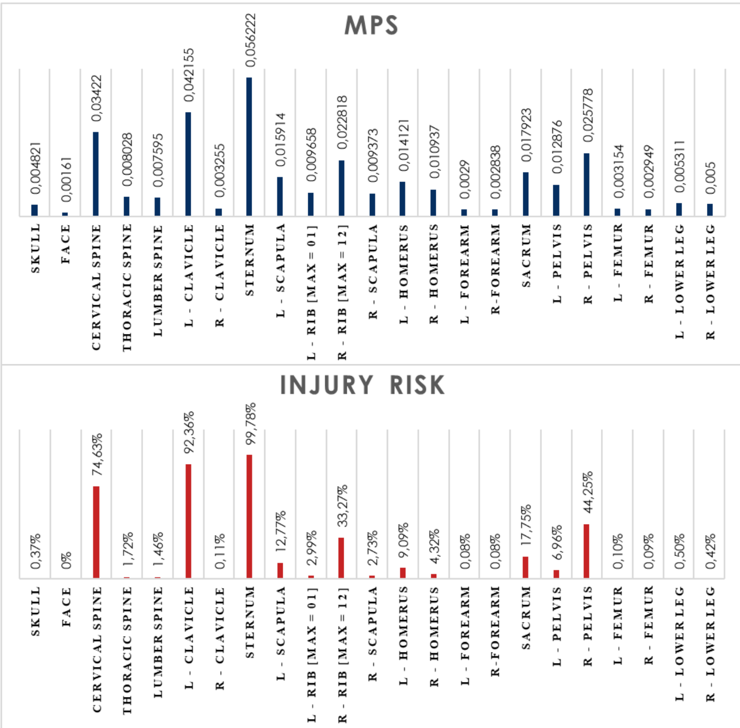


Figure 45 – MPS and IR, Bones – THUMS v4 Frontal Sled

ORGANS	MPS	CSDM	IR - CSDM
BRAIN	0	0,00179	0,00%
L – LUNG	0,545442	0,087557	50%
R – LUNG	0,405584	0,028741	50%
HEART	0,717238	0,917138	50%
STOMACH	1	0,914676	70,91%
LIVER	1	0,740657	61,30%
AORTA	0,369114	0,01661	0,12%
SPLEEN	1	0,86524	68,64%
L – KIDNEY	0,86139	0,949412	72,32%
R – KIDNEY	0,590674	0,496343	40,14%
INTESTINE	0,945683	0,170487	8%
L - KNEE LIGAMENT	0,152586	0	0%
R - KNEE LIGAMENT	0,124194	0	0%

Table 67 – Injury Risk Parameters, Organs – THUMS v4 Frontal Sled

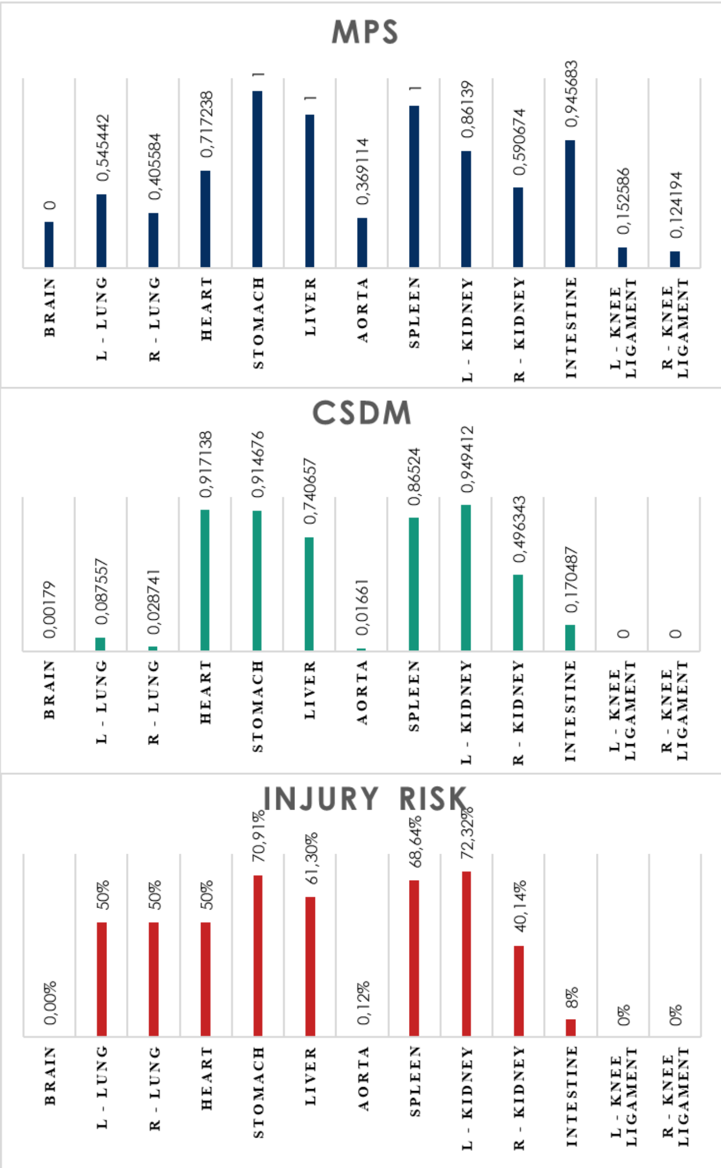


Figure 46 – MPS, CSDM and IR, Organs – THUMS v4 Frontal

BONES	MPS	Injury Risk
SKULL	0,004073	0,22%
FACE	0,002797	0%
CERVICAL SPINE	0,022079	30,67%
THORACIC SPINE	0,095204	100,00%
LUMBER SPINE	0,019298	21,67%
L - CLAVICLE	0,219801	100,00%
R - CLAVICLE	0,40831	100,00%
STERNUM	0,029668	59,03%
L - SCAPULA	0,010851	4,22%
L - RIB [MAX = 03]	0,095595	100,00%
R - RIB [MAX = 01]	0,043573	94,16%
R - SCAPULA	0,008201	1,84%
L - HOMERUS	0,014603	10,01%
R - HOMERUS	0,011111	4,52%
L - FOREARM	0,003078	0,10%
R-FOREARM	0,0021	0,03%
SACRUM	0,001459	0,01%
L - PELVIS	0,016929	15,17%
R - PELVIS	0,009466	2,81%
L - FEMUR	0,00932	0,71%
R - FEMUR	0,005648	0,60%
L - LOWER LEG	0,008771	2,24%
R - LOWER LEG	0,006622	0,97%

Table 78 – Injury Risk Parameters, Bones – THUMS v5 (w/out M_A) Frontal Sled

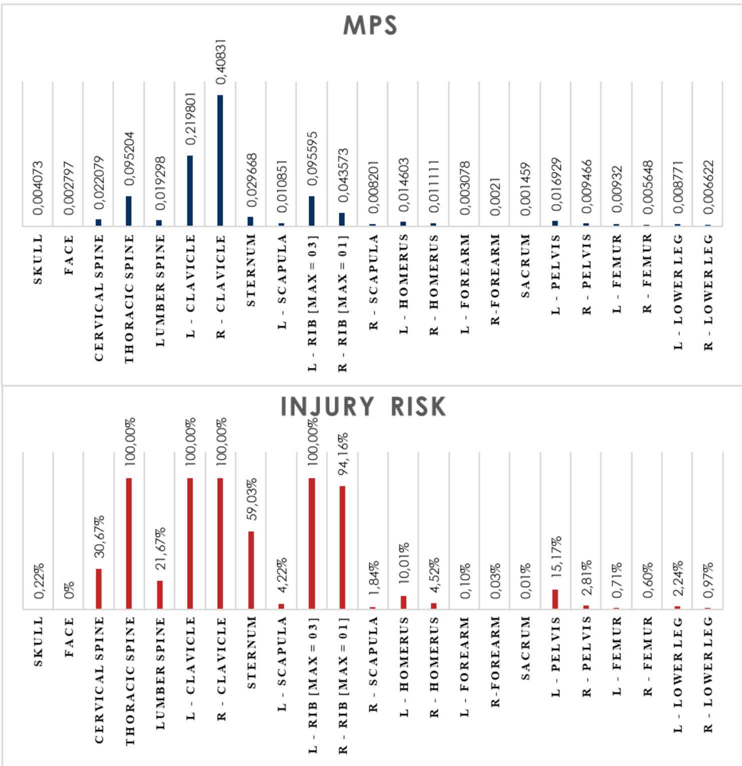


Figure 47 – MPS and IR, Bones – THUMS v5 (w/out M_A) Frontal Sled

ORGANS	MPS	CSDM	IR - CSDM
BRAIN	0	0	0,00%
L - LUNG	0,567586	0,051433	50%
R - LUNG	0,510326	0,014757	50%
HEART	0,576201	0,356159	0%
STOMACH	0	0,104614	3,28%
LIVER	0,333498	0,006641	0,02%
AORTA	0,521965	0,04487	0,73%
SPLEEN	0	0,490486	39,54%
L - KIDNEY	0,324655	0,014943	0,10%
R - KIDNEY	0,297942	0,052934	0,98%
INTESTINE	0,217358	0	0%
L - KNEE LIGAMENT	0,074685	0	0%
R - KNEE LIGAMENT	0,075231	0	0%

Table 88 – Injury Risk Parameters, Organs – THUMS v5 (w/out M_A) Frontal Sled

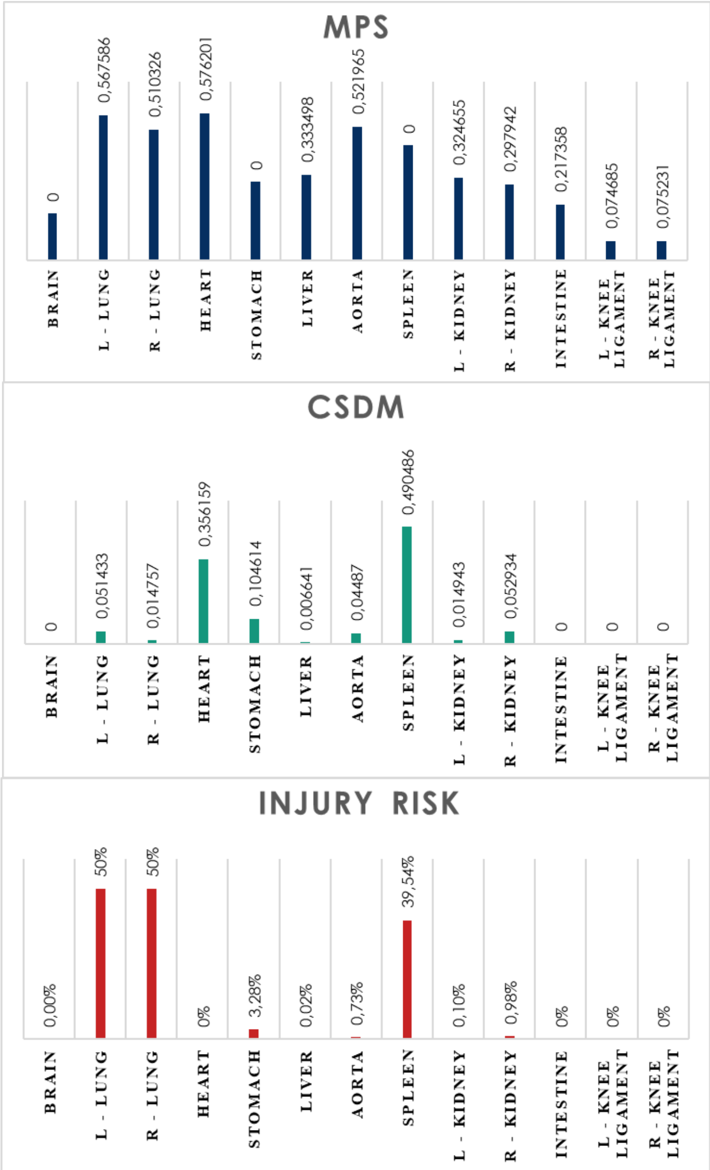


Figure 48 – MPS, CSDM and IR, Organs – THUMS v5 (w/out M_A) Frontal Sled

BONES	MPS	Injury Risk
SKULL	0,002812	0,07%
FACE	0,002329	0%
CERVICAL SPINE	0,008138	1,79%
THORACIC SPINE	0,112047	100,00%
LUMBER SPINE	0,020045	23,95%
L - CLAVICLE	0,169314	100,00%
R - CLAVICLE	0,304145	100,00%
STERNUM	0,026151	45,67%
L - SCAPULA	0,011069	4,47%
L - RIB [MAX = 01]	0,031432	65,42%
R - RIB [MAX = 01]	0,027667	51,47%
R - SCAPULA	0,006238	0,81%
L - HOMERUS	0,015015	10,83%
R - HOMERUS	0,014909	10,62%
L - FOREARM	0,002495	0,05%
R-FOREARM	0,002735	0,07%
SACRUM	0,001388	0,01%
L - PELVIS	0,033281	71,68%
R - PELVIS	0,014521	9,85%
L - FEMUR	0,0082	1,84%
R - FEMUR	0,005141	0,42%
L - LOWER LEG	0,011735	5,31%
R - LOWER LEG	0,006528	0,93%

Table 99 – Injury Risk Parameters, Bones – THUMS v5 (w/ M_A) Frontal Sled

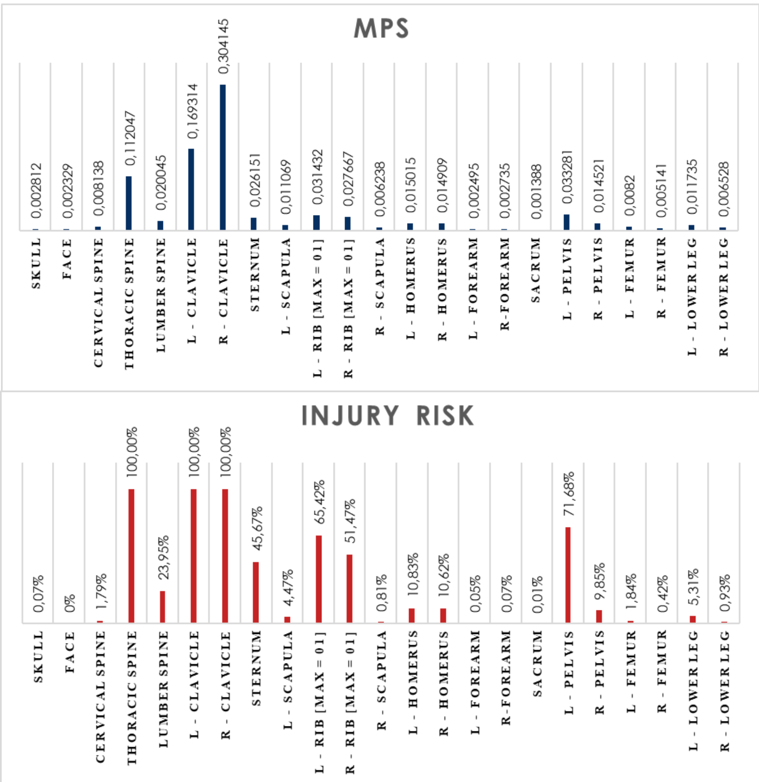


Figure 49 – MPS and IR, Bones – THUMS v5 (w/ M_A) Frontal Sled

ORGANS	MPS	CSDM	IR - CSDM
BRAIN	0	0	0,00%
L - LUNG	0,58506	0,043284	50%
R - LUNG	0,468295	0,004208	50%
HEART	0,634522	0,334395	0%
STOMACH	0	0,285242	18,04%
LIVER	0,257643	0	0,00%
AORTA	0,453832	0,061773	1,29%
SPLEEN	0	0,162044	7,04%
L - KIDNEY	0,301897	0,003254	0,01%
R - KIDNEY	0,274475	0,035397	0,48%
INTESTINE	0,214784	0	0%
L - KNEE LIGAMENT	0,061294	0	0%
R - KNEE LIGAMENT	0,073999	0	0%

Table 20 – Injury Risk Parameters, Organs – THUMS v5 (w/ M_A) Frontal Sled

Figure 50 – MPS, CSDM and IR, Organs – THUMS v5 (w/ M_A) Frontal Sled

Version 5 w/out Muscle Activation vs Version 5 w/ Muscle Activation

BONES	NO_MA	MA
SKULL	0,004073	0,002812
FACE	0,002797	0,002329
CERVICAL SPINE	0,022079	0,008138
THORACIC SPINE	0,095204	0,112047
LUMBER SPINE	0,019298	0,020045
L – CLAVICLE	0,219801	0,169314
R – CLAVICLE	0,40831	0,304145
STERNUM	0,029668	0,026151
L – SCAPULA	0,010851	0,011069
L - RIB [MAX = 03]	0,095595	0,031432
R - RIB [MAX = 01]	0,043573	0,027667
R – SCAPULA	0,008201	0,006238
L – HOMERUS	0,014603	0,015015
R – HOMERUS	0,011111	0,014909
L – FOREARM	0,003078	0,002495
R-FOREARM	0,0021	0,002735
SACRUM	0,001459	0,001388
L – PELVIS	0,016929	0,033281
R – PELVIS	0,009466	0,014521
L – FEMUR	0,00932	0,0082
R – FEMUR	0,005648	0,005141
L - LOWER LEG	0,008771	0,011735
R - LOWER LEG	0,006622	0,006528

Table 21 – MPS Bones – THUMS v5 w/out M_A vs THUMS v5 w/ M_A

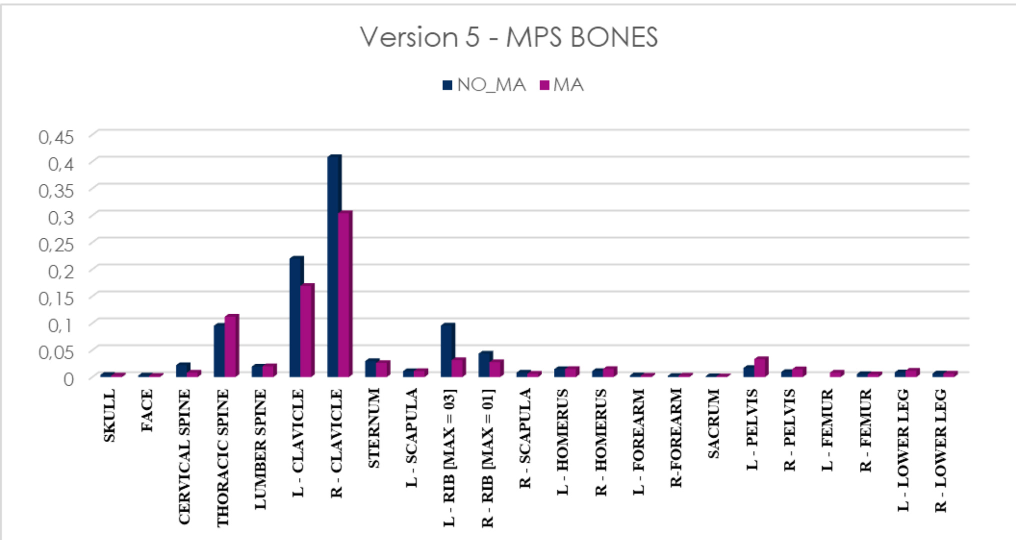
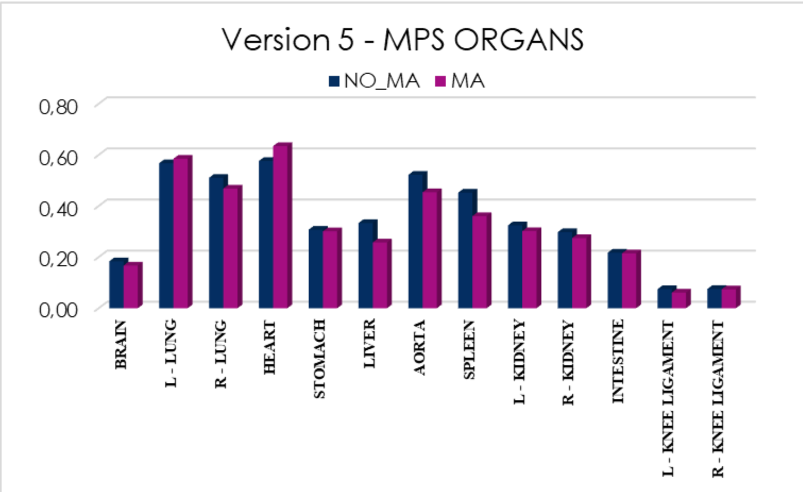


Figure 51 – MPS, Bones – THUMS v5 (w/out M_A) vs THUMS v5 (w/ M_A)

ORGANS	MPS NO_MA	MPS MA	CSDM NO_MA	CSDM MA
BRAIN	0	0	0	0
L – LUNG	0,567586	0,58506	0,051433	0,043284
R – LUNG	0,510326	0,468295	0,014757	0,004208
HEART	0,576201	0,634522	0,356159	0,334395
STOMACH	0	0	0,104614	0,285242
LIVER	0,333498	0,257643	0,006641	0
AORTA	0,521965	0,453832	0,04487	0,061773
SPLEEN	0	0	0,490486	0,162044
L – KIDNEY	0,324655	0,301897	0,014943	0,003254
R – KIDNEY	0,297942	0,274475	0,052934	0,035397
INTESTINE	0,217358	0,214784	0	0
L - KNEE LIGAMENT	0,074685	0,061294	0	0
R - KNEE LIGAMENT	0,075231	0,073999	0	0

Table 22 – MPS, CSDM Organs – THUMS v5 w/out M_A vs THUMS v5 w/ M_A



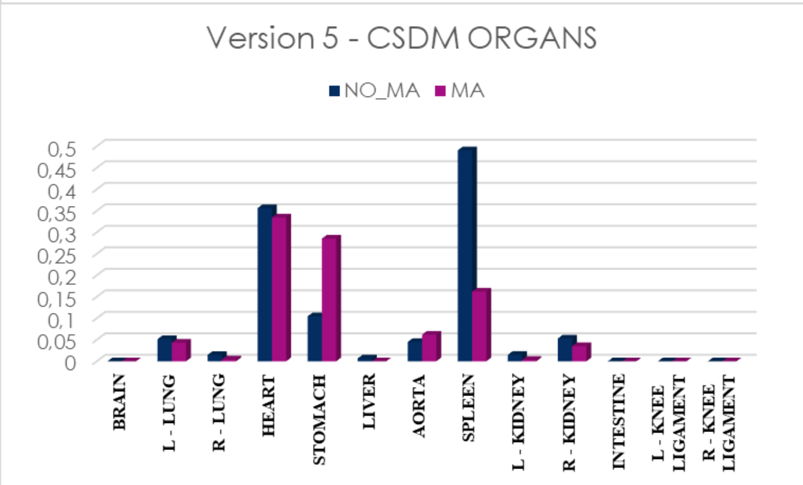


Figure 52 – MPS and CSDM, Organs – THUMS v5 (w/out M_A) vs THUMS v5 (w/ M_A)

BONES	MPS	Injury Risk
SKULL	0,00442	0,29%
FACE	0	0%
CERVICAL SPINE	0,005985	0,72%
THORACIC SPINE	0,00654	0,93%
LUMBER SPINE	0,006842	1,07%
L - CLAVICLE	0,071664	100,00%
R - CLAVICLE	0,002207	0,04%
STERNUM	0,037131	82,70%
L - SCAPULA	0,008887	2,33%
L - RIB [MAX = 03]	0,007523	1,42%
R - RIB [MAX = 12]	0,023592	36,07%
R - SCAPULA	0,015436	11,72%
L - HOMERUS	0,012704	6,69%
R - HOMERUS	0,010877	4,25%
L - FOREARM	0,003028	0,09%
R-FOREARM	0,002284	0,04%
SACRUM	0,023299	35,00%
L - PELVIS	0,015806	12,53%
R - PELVIS	0,024078	37,85%
L - FEMUR	0,003448	0,14%
R - FEMUR	0,007407	1,35%
L - LOWER LEG	0,004567	0,32%
R - LOWER LEG	0,00433	0,27%

Table 23 – Injury Risk Parameters, Bones – THUMS v6 (w/out M_A) Frontal Sled

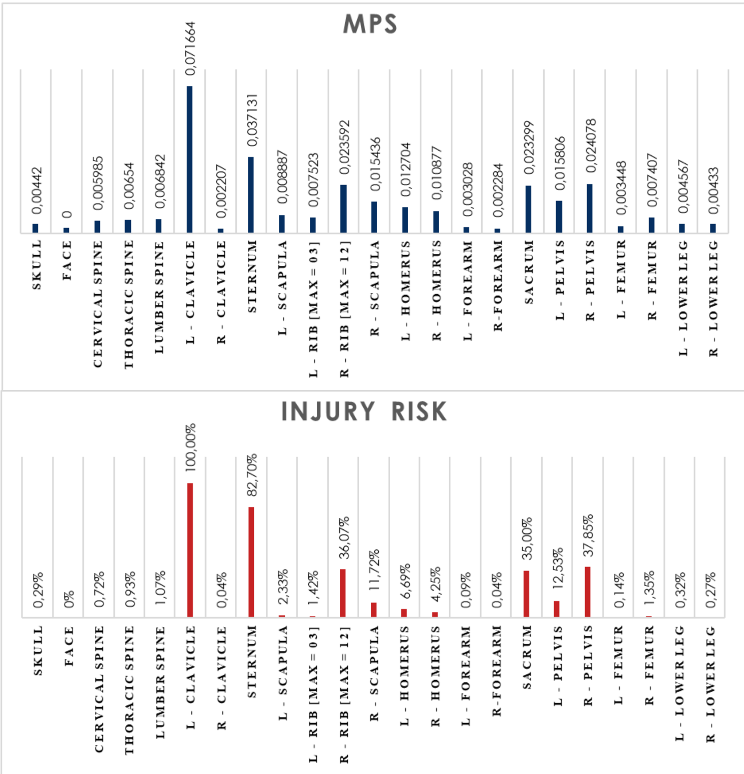


Figure 53 – MPS and IR, Bones – THUMS v6 (w/out M_A) Frontal Sled

ORGANS	MPS	CSDM	IR - CSDM
BRAIN	0	0,004078	0,00%
L - LUNG	0,464068	0,108537	50%
R - LUNG	0,296654	0,007315	50%
HEART	0,617613	0,868818	0%
STOMACH	1	0,933366	71,69%
LIVER	0,957129	0,741793	61,38%
AORTA	0,371627	0,01332	0,25%
SPLEEN	1	0,921355	71,19%
L - KIDNEY	0,84215	0,964232	72,87%
R - KIDNEY	0,541462	0,428138	33,03%
INTESTINE	0,884972	0,184171	9%
L - KNEE LIGAMENT	0,181795	0	0%
R - KNEE LIGAMENT	0,152431	0	0%

Table 24 – Injury Risk Parameters, Organs – THUMS v6 (w/out M_A) Frontal Sled

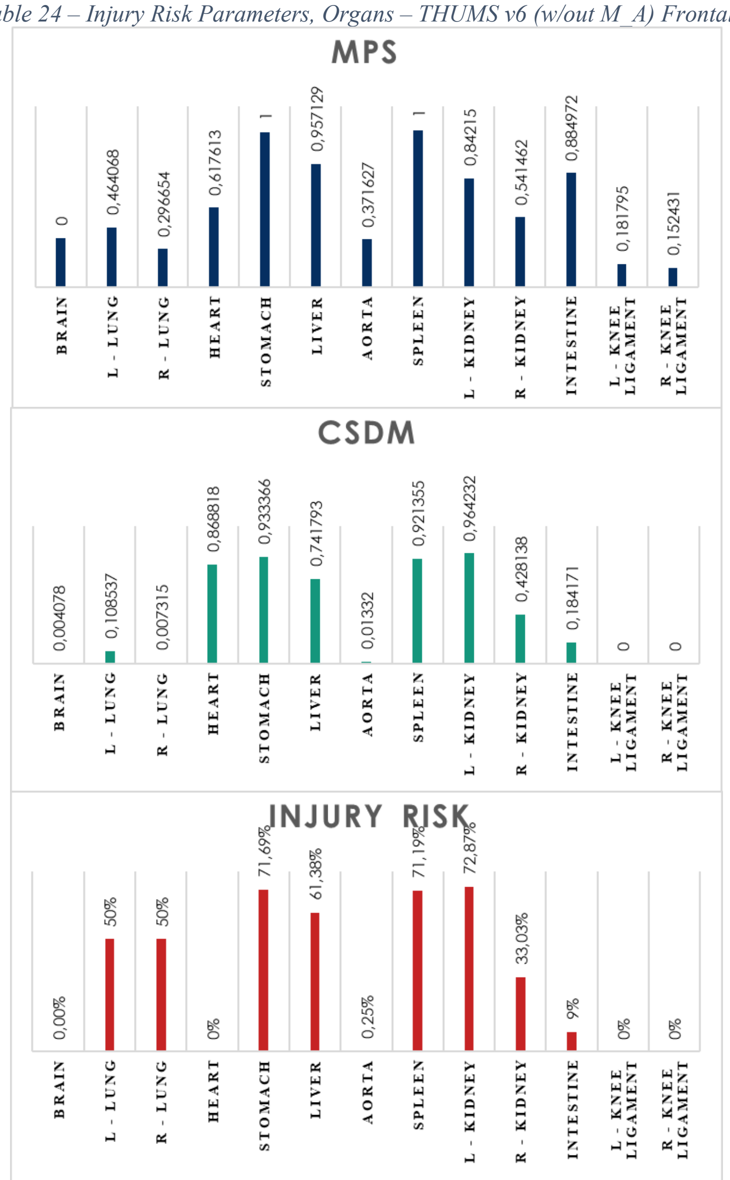


Figure 54 – MPS, CSDM and IR, Organs – THUMS v6 (w/out M_A) Frontal Sled

BONES	MPS	Injury Risk
SKULL	0,00442	0,29%
FACE	0	0%
CERVICAL SPINE	0,005985	0,72%
THORACIC SPINE	0,00654	0,93%
LUMBER SPINE	0,006842	1,07%
L - CLAVICLE	0,071664	100,00%
R - CLAVICLE	0,002207	0,04%
STERNUM	0,037131	82,70%
L - SCAPULA	0,008887	2,33%
L - RIB [MAX = 03]	0,007523	1,42%
R - RIB [MAX = 12]	0,023592	36,07%
R - SCAPULA	0,015436	11,72%
L - HOMERUS	0,012704	6,69%
R - HOMERUS	0,010877	4,25%
L - FOREARM	0,003028	0,09%
R-FOREARM	0,002284	0,04%
SACRUM	0,023299	35,00%
L - PELVIS	0,015806	12,53%
R - PELVIS	0,024078	37,85%
L - FEMUR	0,003448	0,14%
R - FEMUR	0,007407	1,35%
L - LOWER LEG	0,004567	0,32%
R - LOWER LEG	0,00433	0,27%

Table 25 – Injury Risk Parameters, Bones – THUMS v6 (w/ M_A) Frontal Sled

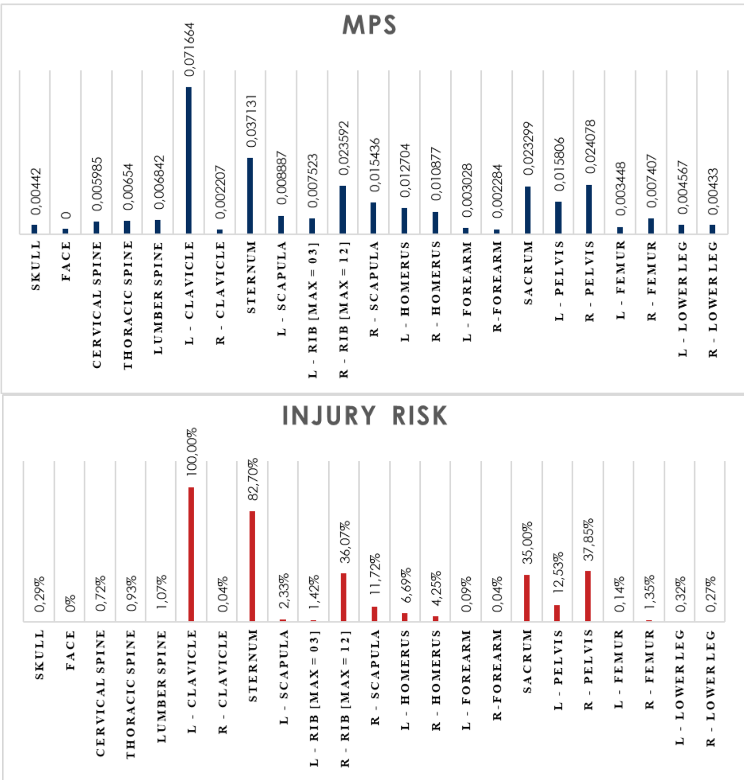


Figure 55 – MPS and IR, Bones – THUMS v6 (w/ M_A) Frontal Sled

ORGANS	MPS	CSDM	IR - CSDM
BRAIN	1	0,000468	0,00%
L – LUNG	0,540612	0,197017	50%
R – LUNG	0,439706	0,066071	50%
HEART	0,72123	0,906669	0%
STOMACH	1	0,937664	71,86%
LIVER	1	0,720706	59,90%
AORTA	0,432393	0,022601	0,21%
SPLEEN	1	0,869351	68,84%
L – KIDNEY	0,861058	0,971362	73,12%
R – KIDNEY	0,51175	0,280432	17,56%
INTESTINE	1	0,19189	9%
L - KNEE LIGAMENT	0,1111	0	0%
R - KNEE LIGAMENT	0,102374	0	0%

Table 25 – Injury Risk Parameters, Bones – THUMS v6 (w/ M_A) Frontal Sled

Figure 56 – MPS, CSDM and IR, Organs – THUMS v6 (w/ M_A) Frontal Sled

Version 6 w/out Muscle Activation vs Version 6 w/ Muscle Activation

BONES	NO_MA	MA
SKULL	0,00442	0,003634
FACE	0	0,00249
CERVICAL SPINE	0,005985	0,01709
THORACIC SPINE	0,00654	0,040057
LUMBER SPINE	0,006842	0,043942
L – CLAVICLE	0,071664	0,027192
R – CLAVICLE	0,002207	0,008546
STERNUM	0,037131	0,054526
L – SCAPULA	0,008887	0,015654
L - RIB [MAX = 03]	0,007523	0,015712
R - RIB [MAX = 12]	0,023592	0,012445
R – SCAPULA	0,015436	0,025438
L – HOMERUS	0,012704	0,005101
R – HOMERUS	0,010877	0,010404
L – FOREARM	0,003028	0,00278
R-FOREARM	0,002284	0,007062
SACRUM	0,023299	0,007011
L – PELVIS	0,015806	0,014425
R – PELVIS	0,024078	0,025168
L – FEMUR	0,003448	0,003633
R – FEMUR	0,007407	0,002145
L - LOWER LEG	0,004567	0,006584
R - LOWER LEG	0,00433	0,006542

Table 26 – MPS Bones – THUMS v6 w/ M_A vs THUMS v6 w/out M_A

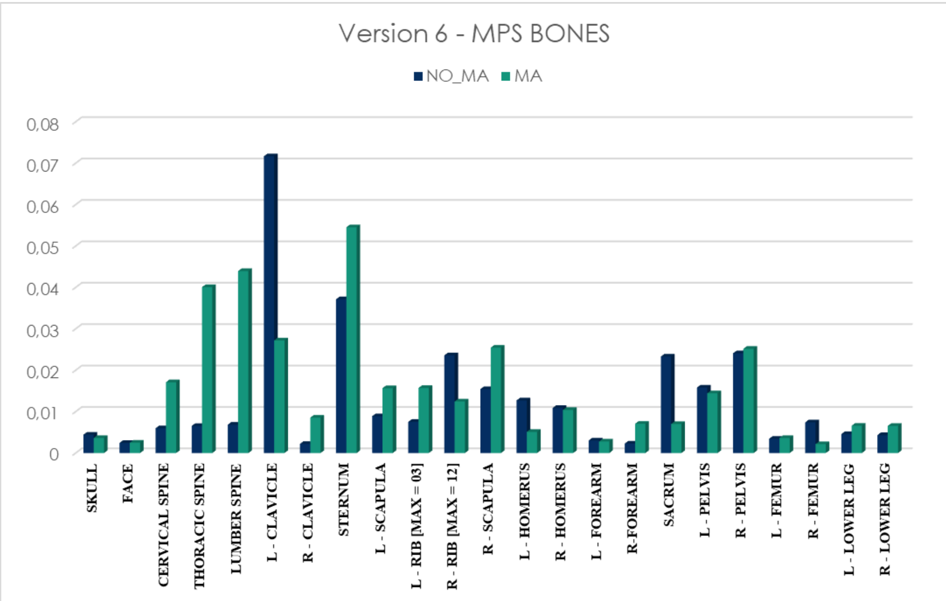


Figure 57 – MPS, Bones – THUMS v6 (w/out M_A) vs THUMS v6 (w/ M_A)

ORGANS	MPS NO_MA	MPS MA	CSDM NO_MA	CSDM MA
BRAIN	0	1	0,004078	0,000468
L – LUNG	0,464068	0,540612	0,108537	0,197017
R – LUNG	0,296654	0,439706	0,007315	0,066071
HEART	0,617613	0,72123	0,868818	0,906669
STOMACH	1	1	0,933366	0,937664
LIVER	0,957129	1	0,741793	0,720706
AORTA	0,371627	0,432393	0,01332	0,022601
SPLEEN	1	1	0,921355	0,869351
L – KIDNEY	0,84215	0,861058	0,964232	0,971362
R – KIDNEY	0,541462	0,51175	0,428138	0,280432
INTESTINE	0,884972	1	0,184171	0,19189
L - KNEE LIGAMENT	0,181795	0,1111	0	0
R - KNEE LIGAMENT	0,152431	0,102374	0	0

Table 27 – MPS, CSDM Organs – THUMS v6 w/out M_A vs THUMS v6 w/ M_A

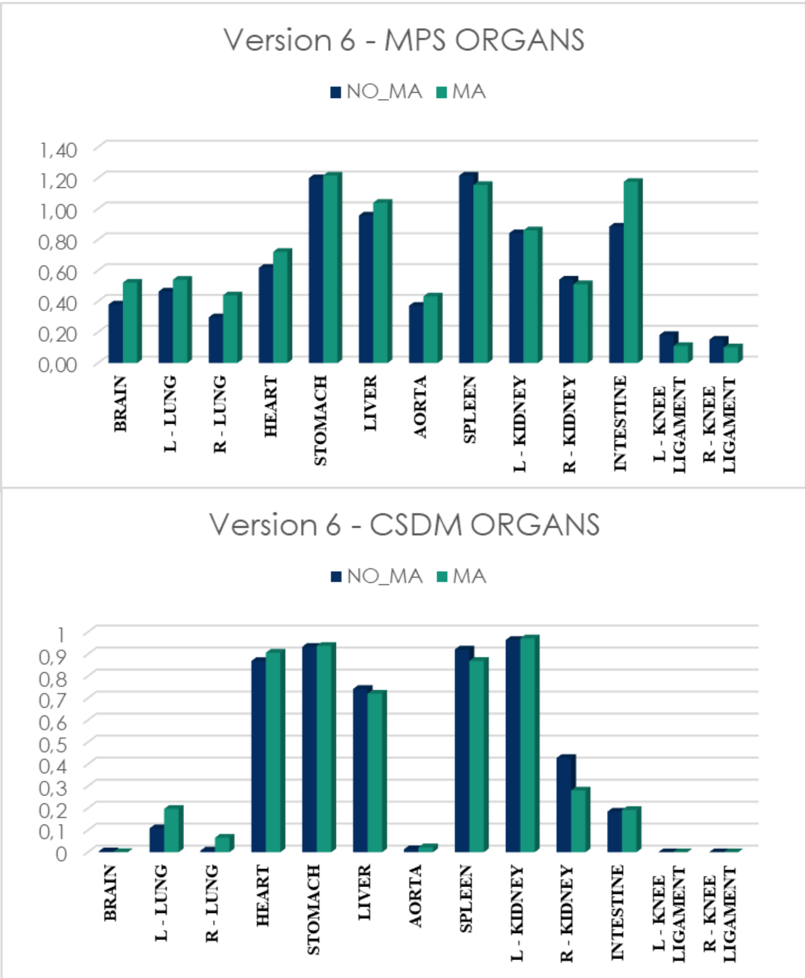


Figure 58 – MPS and CSDM, Organs – THUMS v6 (w/out M_A) vs THUMS v6 (w/ M_A)

Comparison Between all Versions

MPS BONES	V4	V5	V5_MA	V6	V6_MA
SKULL	0,004821	0,004073	0,002812	0,00442	0,003634
FACE	0,00161	0,002797	0,002329	0	0,00249
CERVICAL SPINE	0,03422	0,022079	0,008138	0,005985	0,01709
THORACIC SPINE	0,008028	0,095204	0,112047	0,00654	0,040057
LUMBER SPINE	0,007595	0,019298	0,020045	0,006842	0,043942
L - CLAVICLE	0,042155	0,219801	0,169314	0,071664	0,027192
R - CLAVICLE	0,003255	0,40831	0,304145	0,002207	0,008546
STERNUM	0,056222	0,029668	0,026151	0,037131	0,054526
L - SCAPULA	0,015914	0,010851	0,011069	0,008887	0,015654
L - RIB [MAX = 01]	0,009658	0,095595	0,031432	0,007523	0,015712
R - RIB [MAX = 12]	0,022818	0,043573	0,027667	0,023592	0,012445
R - SCAPULA	0,009373	0,008201	0,006238	0,015436	0,025438
L - HOMERUS	0,014121	0,014603	0,015015	0,012704	0,005101
R - HOMERUS	0,010937	0,011111	0,014909	0,010877	0,010404
L - FOREARM	0,0029	0,003078	0,002495	0,003028	0,00278
R-FOREARM	0,002838	0,0021	0,002735	0,002284	0,007062
SACRUM	0,017923	0,001459	0,001388	0,023299	0,007011
L - PELVIS	0,012876	0,016929	0,033281	0,015806	0,014425
R - PELVIS	0,025778	0,009466	0,014521	0,024078	0,025168
L - FEMUR	0,003154	0,00932	0,0082	0,003448	0,003633
R - FEMUR	0,002949	0,005648	0,005141	0,007407	0,002145
L - LOWER LEG	0,005311	0,008771	0,011735	0,004567	0,006584
R - LOWER LEG	0,005	0,006622	0,006528	0,00433	0,006542

Table 28 – MPS Bones – THUMS v4 vs THUMS v5 vs THUMS v6

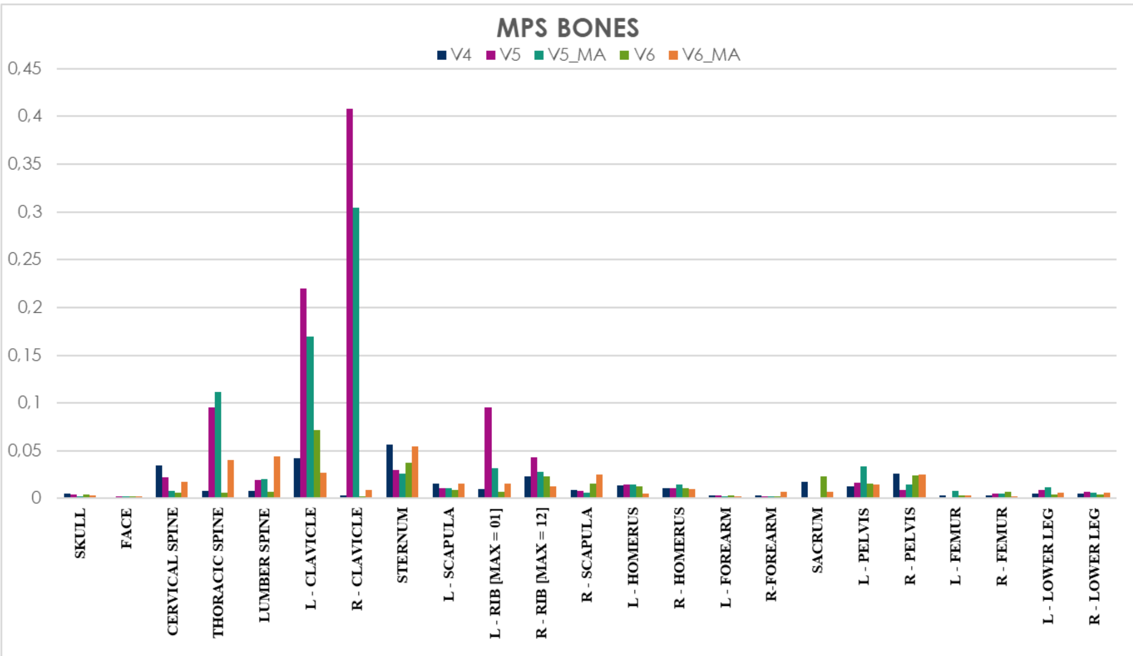


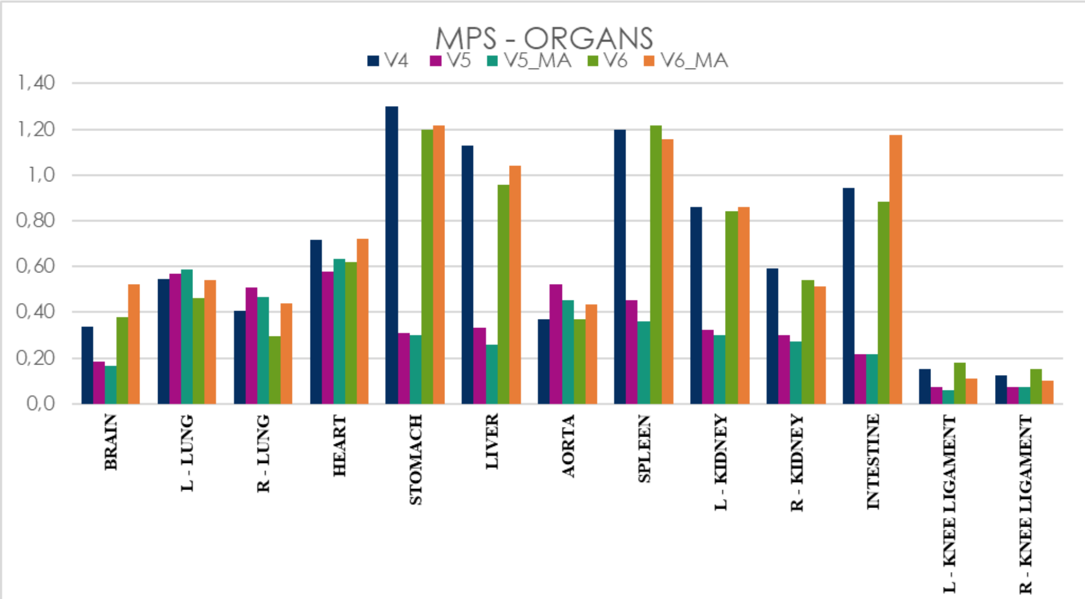
Figure 59 – MPS, Bones – THUMS v4 vs THUMS v5 vs THUMS v6

MPS ORGANS	V4	V5	V5_MA	V6	V6_MA
BRAIN	0	0	0	0	1
L – LUNG	0,545442	0,567586	0,58506	0,464068	0,540612
R – LUNG	0,405584	0,510326	0,468295	0,296654	0,439706
HEART	0,717238	0,576201	0,634522	0,617613	0,72123
STOMACH	1	0	0	1	1
LIVER	1	0,333498	0,257643	0,957129	1
AORTA	0,369114	0,521965	0,453832	0,371627	0,432393
SPLEEN	1	0	0	1	1
L – KIDNEY	0,86139	0,324655	0,301897	0,84215	0,861058
R – KIDNEY	0,590674	0,297942	0,274475	0,541462	0,51175
INTESTINE	0,945683	0,217358	0,214784	0,884972	1
L - KNEE LIGAMENT	0,152586	0,074685	0,061294	0,181795	0,1111
R - KNEE LIGAMENT	0,124194	0,075231	0,073999	0,152431	0,102374

Table 29 – MPS Organs – THUMS v4 vs THUMS v5 vs THUMS v6

CSDM ORGANS	V4	V5	V5_MA	V6	V6_MA
BRAIN	0,00179	0	0	0,004078	0,000468
L - LUNG	0,087557	0,051433	0,043284	0,108537	0,197017
R - LUNG	0,028741	0,014757	0,004208	0,007315	0,066071
HEART	0,917138	0,356159	0,334395	0,868818	0,906669
STOMACH	0,914676	0,104614	0,285242	0,933366	0,937664
LIVER	0,740657	0,006641	0	0,741793	0,720706
AORTA	0,01661	0,04487	0,061773	0,01332	0,022601
SPLEEN	0,86524	0,490486	0,162044	0,921355	0,869351
L - KIDNEY	0,949412	0,014943	0,003254	0,964232	0,971362
R - KIDNEY	0,496343	0,052934	0,035397	0,428138	0,280432
INTESTINE	0,170487	0	0	0,184171	0,19189
L - KNEE LIGAMENT	0	0	0	0	0
R - KNEE LIGAMENT	0	0	0	0	0

Table 30 – CSDM Organs – THUMS v4 vs THUMS v5 vs THUMS v6



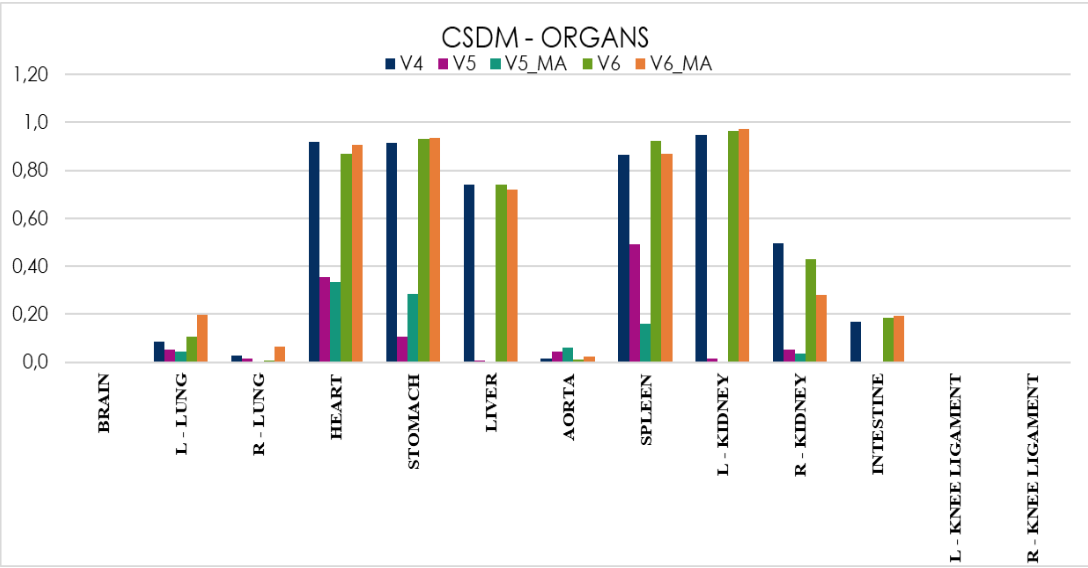


Figure 61 – MPS and CSDM, Organs – THUMS v4 vs THUMS v5 vs THUMS v6

Second Scenario

BONES	MPS	Injury Risk
SKULL	0,002666	0,06%
FACE	0,000813	0%
CERVICAL SPINE	0,004924	0,40%
THORACIC SPINE	0,006021	0,73%
LUMBER SPINE	0,002683	0,06%
L - CLAVICLE	0,001952	0,02%
R - CLAVICLE	0,000927	0,00%
STERNUM	0,002552	0,05%
L - SCAPULA	0,00353	0,15%
L - RIB [MAX = 01]	0,003311	0,12%
R - RIB [MAX = 12]	0,003989	0,21%
R - SCAPULA	0,004813	0,37%
L - HOMERUS	0,002415	0,05%
R - HOMERUS	0,002154	0,03%
L - FOREARM	0,001758	0,02%
R-FOREARM	0,000837	0,00%
SACRUM	0,001974	0,03%
L - PELVIS	0,016359	13,79%
R - PELVIS	0,00299	0,09%
L - FEMUR	0,002978	0,09%
R - FEMUR	0,001443	0,01%
L - LOWER LEG	0,001636	0,01%
R - LOWER LEG	0,001359	0,01%

Table 32 – Injury Risk Parameters, Bones – THUMS v4 Fall from Seated

Figure 61 – MPS and IR, Bones – THUMS v4 Fall from Seated

ORGANS	MPS	CSDM	IR - CSDM
BRAIN	0	0,001144	0,00%
L - LUNG	0,166061	0	0%
R - LUNG	0,229518	0	0%
HEART	0,472448	0,021881	0%
STOMACH	1	0,056528	1,10%
LIVER	1	0,014466	0,10%
AORTA	0,167095	0	0,00%
SPLEEN	0	0,002454	0,00%
L - KIDNEY	0,306093	0,003862	0,01%
R - KIDNEY	0,382447	0,005446	0,02%
INTESTINE	0,530731	0,006083	0%
L - KNEE LIGAMENT	0,127159	0	0%
R - KNEE LIGAMENT	0,082552	0	0%

Table 33 – Injury Risk Parameters, Organs – THUMS v4 Fall from Seated

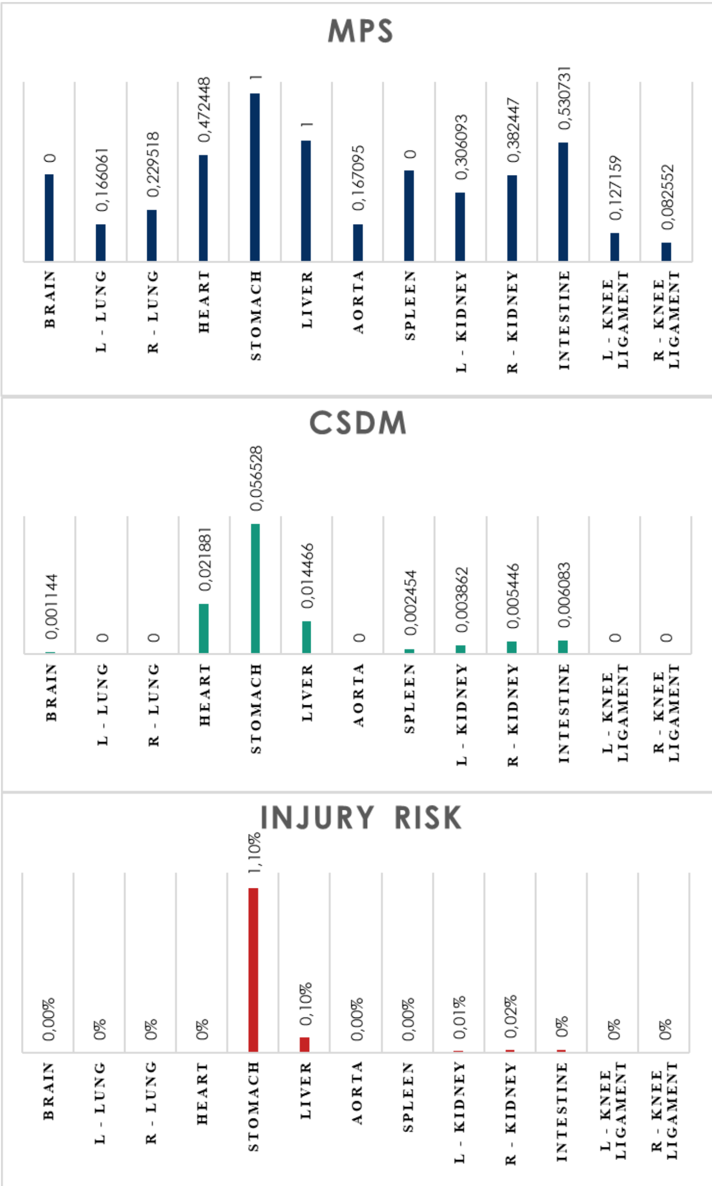


Figure 62 – MPS, CSDM and IR, Organs – THUMS v4 Fall from Seated

BONES	MPS	Injury Risk
SKULL	0,001006	0,00%
FACE	0,001628	0%
CERVICAL SPINE	0,005854	0,67%
THORACIC SPINE	0,048473	98,01%
LUMBER SPINE	0,016008	12,98%
L - CLAVICLE	0,06965	100,00%
R - CLAVICLE	0,070586	100,00%
STERNUM	0,016118	13,23%
L - SCAPULA	0,002892	0,08%
L - RIB [MAX = 01]	0,006944	1,12%
R - RIB [MAX = 11]	0,025013	41,35%
R - SCAPULA	0,002785	0,07%
L - HOMERUS	0,004518	0,31%
R - HOMERUS	0,005586	0,58%
L - FOREARM	0,004368	0,28%
R-FOREARM	0,006551	0,94%
SACRUM	0,001456	0,01%
L - PELVIS	0,038766	86,43%
R - PELVIS	0,006142	0,77%
L - FEMUR	0,003326	0,12%
R - FEMUR	0,003666	0,16%
L - LOWER LEG	0,000968	0,00%
R - LOWER LEG	0,001062	0,00%

Table 34 – Injury Risk Parameters, Bones – THUMS v5 (w/out M_A) Fall from Seated

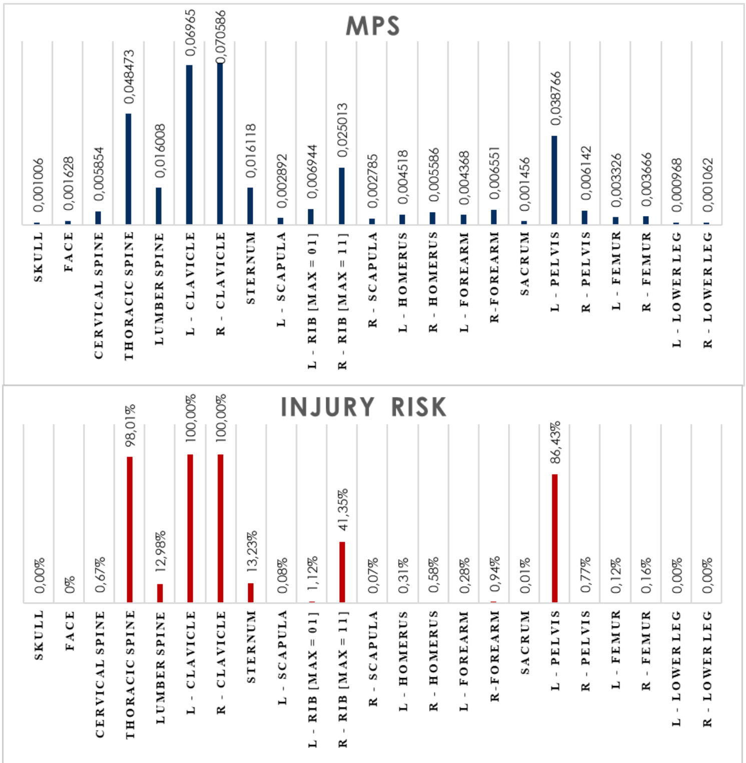


Figure 63 – MPS and IR, Bones – THUMS v5 (w/out M_A) Fall from Seated

ORGANS	MPS	CSDM	IR – CSDM
BRAIN	0,090585	0	0%
L - LUNG	0,157899	0	0%
R - LUNG	0,221305	0	0%
HEART	0,195867	0	0%
STOMACH	0,194145	0	0%
LIVER	0,147553	0	0%
AORTA	0,194925	0	0%
SPLEEN	0,176274	0	0%
L - KIDNEY	0,17573	0	0%
R - KIDNEY	0,180916	0	0%
INTESTINE	0,183479	0	0%
L - KNEE LIGAMENT	0,038913	0	0%
R - KNEE LIGAMENT	0,089941	0	0%

Table 35 – Injury Risk Parameters, Organs – THUMS v5 (w/out M_A) Fall from Seated

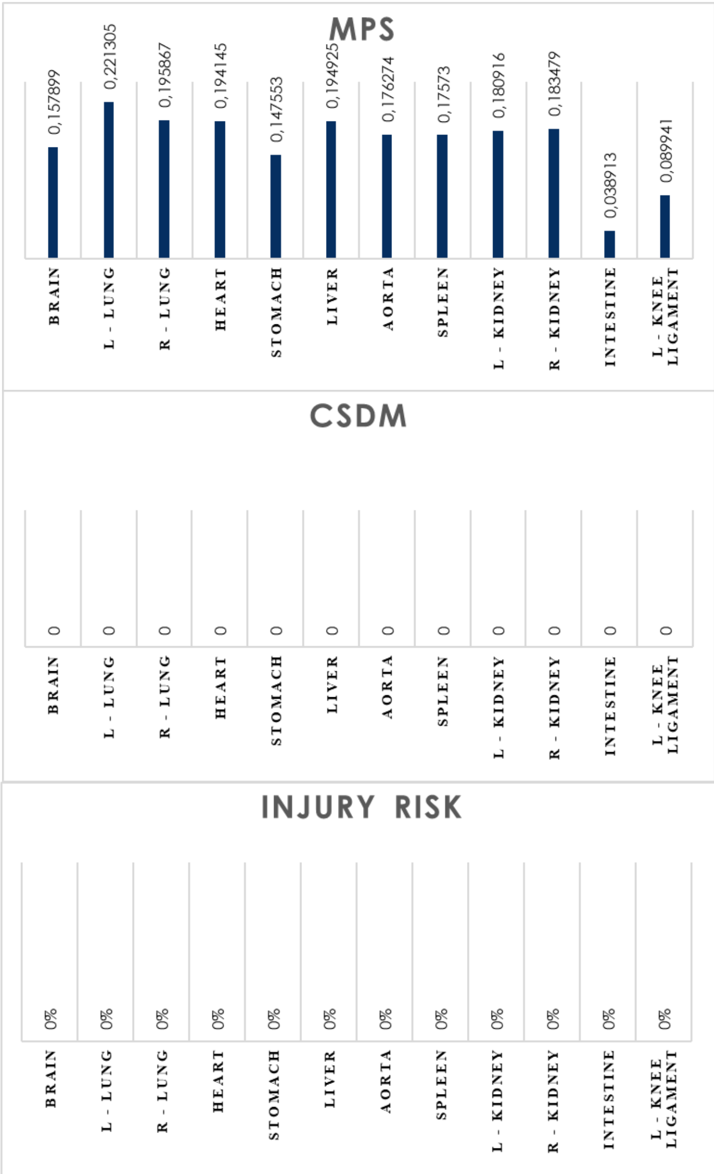


Figure 64 – MPS, CSDM and IR, Organs – THUMS v5 (w/out M_A) Fall from Seated

BONES	MPS	Injury Risk
SKULL	0,000833	0,00%
FACE	0,001687	0%
CERVICAL SPINE	0,00567	0,61%
THORACIC SPINE	0,025471	43,08%
LUMBER SPINE	0,01479	10,38%
L - CLAVICLE	0,06922	100,00%
R - CLAVICLE	0,088505	100,00%
STERNUM	0,002593	0,06%
L - SCAPULA	0,001876	0,02%
L - RIB [MAX = 04]	0,007388	1,34%
R - RIB [MAX = 11]	0,023807	36,85%
R - SCAPULA	0,002533	0,05%
L - HOMERUS	0,004863	0,38%
R - HOMERUS	0,004542	0,31%
L - FOREARM	0,00402	0,22%
R-FOREARM	0,00417	0,24%
SACRUM	0,001525	0,01%
L - PELVIS	0,004048	0,22%
R - PELVIS	0,004063	0,22%
L - FEMUR	0,003384	0,13%
R - FEMUR	0,003497	0,14%
L - LOWER LEG	0,00092	0,00%
R - LOWER LEG	0,001041	0,00%

Table 36 – Injury Risk Parameters, Bones – THUMS v5 (w/ M_A) Fall from Seated

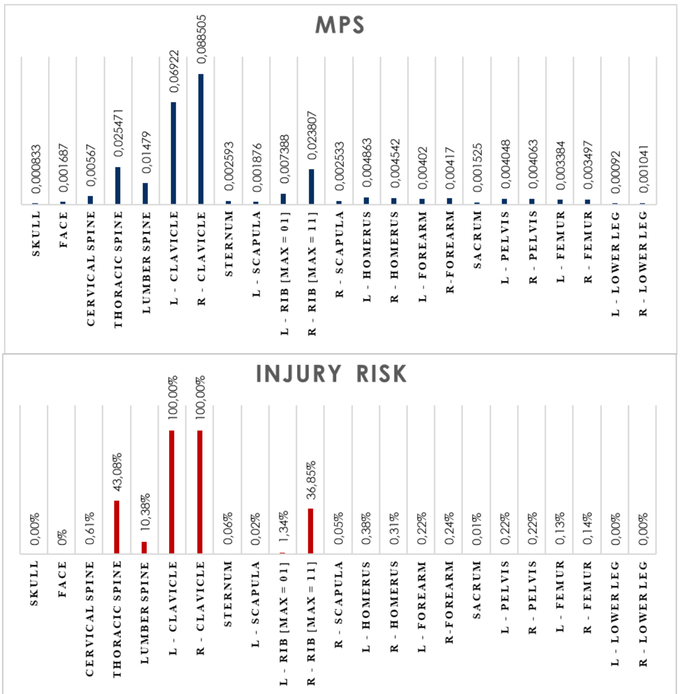


Figure 65 – MPS and IR, Bones – THUMS v5 (w/ M_A) Fall from Seated

ORGANS	MPS	CSDM	IR - CSDM
BRAIN	0	0	0%
L - LUNG	0,186929	0	0%
R - LUNG	0,218324	0	0%
HEART	0,177257	0	0%
STOMACH	0	0	0%
LIVER	0	0	0%
AORTA	0,182943	0	0%
SPLEEN	0	0	0%
L - KIDNEY	0,129197	0	0%
R - KIDNEY	0,147189	0	0%
INTESTINE	0,179449	0	0%
L - KNEE LIGAMENT	0,043978	0	0%
R - KNEE LIGAMENT	0,043208	0	0%

Table 37 – Injury Risk Parameters, Organs – THUMS v5 (w/ M_A) Fall from Seated

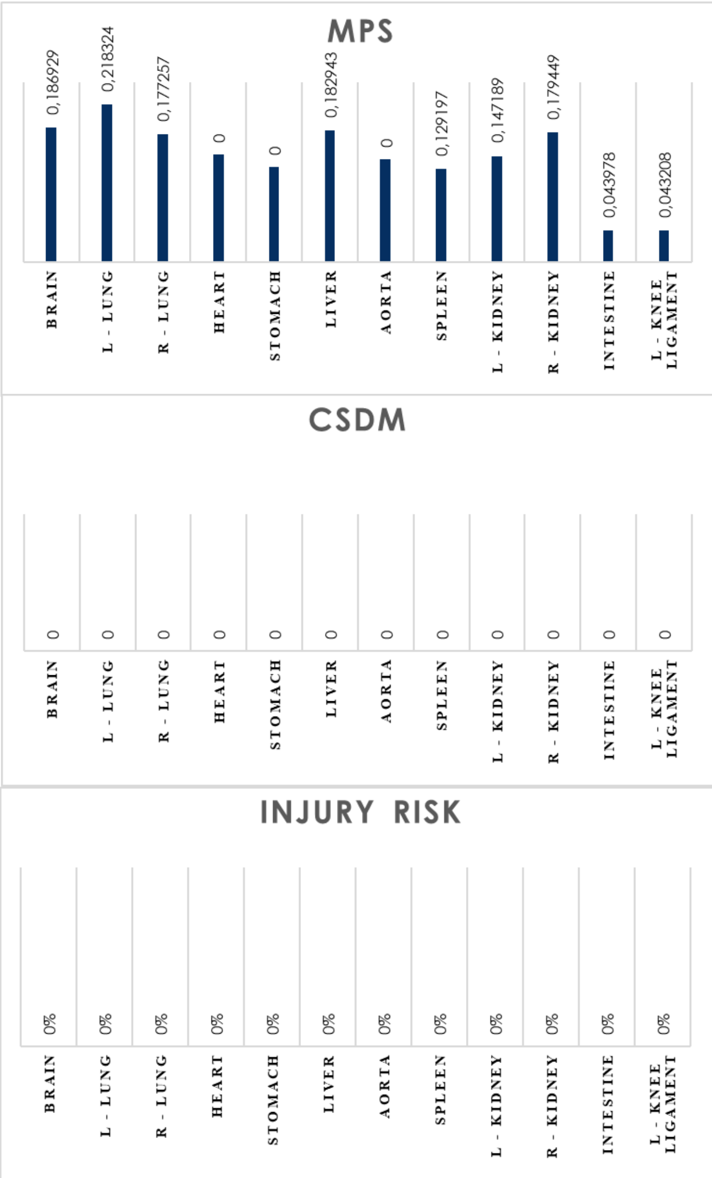


Figure 66 – MPS, CSDM and IR, Organs – THUMS v5 (w/ M_A) Fall from Seated

Version 5 w/out Muscle Activation vs Version 5 w/ Muscle Activation

BONES	NO_MA	MA
SKULL	0,001006	0,000833
FACE	0,001628	0,001687
CERVICAL SPINE	0,005854	0,00567
THORACIC SPINE	0,048473	0,025471
LUMBER SPINE	0,016008	0,01479
L - CLAVICLE	0,06965	0,06922
R - CLAVICLE	0,070586	0,088505
STERNUM	0,016118	0,002593
L - SCAPULA	0,002892	0,001876
L - RIB [MAX = 03]	0,006944	0,007388
R - RIB [MAX = 01]	0,025013	0,023807
R - SCAPULA	0,002785	0,002533
L - HOMERUS	0,004518	0,004863
R - HOMERUS	0,005586	0,004542
L - FOREARM	0,004368	0,00402
R-FOREARM	0,006551	0,00417
SACRUM	0,001456	0,001525
L - PELVIS	0,038766	0,004048
R - PELVIS	0,006142	0,004063
L - FEMUR	0,003326	0,003384
R - FEMUR	0,003666	0,003497
L - LOWER LEG	0,000968	0,00092
R - LOWER LEG	0,001062	0,001041

Table 38 – MPS Bones – THUMS v5 w/out M_A vs THUMS v5 w/ M_A

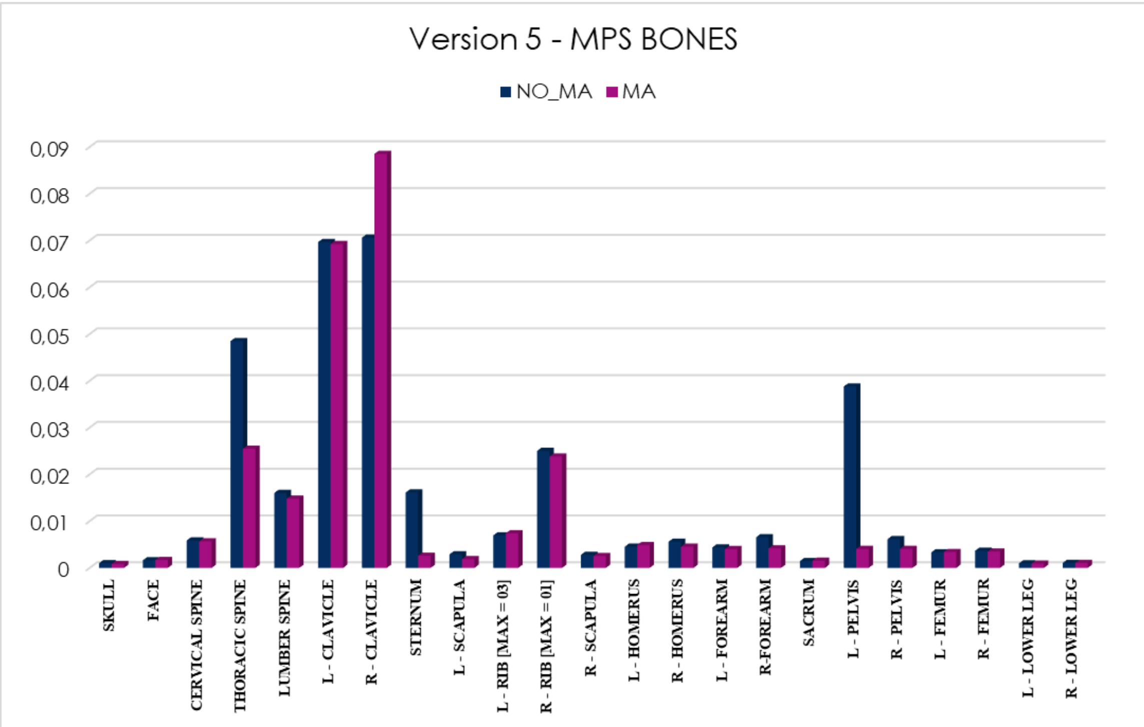


Figure 67 – MPS, Bones – THUMS v5 (w/out M_A) vs THUMS v5 (w/ M_A)

ORGANS	MPS NO_MA	MPS MA	CSDM NO_MA	CSDM_MA
BRAIN	0,090585	0		
L - LUNG	0,157899	0,186929		
R - LUNG	0,221305	0,218324		
HEART	0,195867	0,177257		
STOMACH	0,194145	0		
LIVER	0,147553	0		
AORTA	0,194925	0,182943		
SPLEEN	0,176274	0		
L - KIDNEY	0,17573	0,129197		
R - KIDNEY	0,180916	0,147189		
INTESTINE	0,183479	0,179449		
L - KNEE LIGAMENT	0,038913	0,043978		
R - KNEE LIGAMENT	0,089941	0,043208		

Table 39 – MPS, CSDM Organs – THUMS v5 w/out M_A vs THUMS v5 w/ M_A

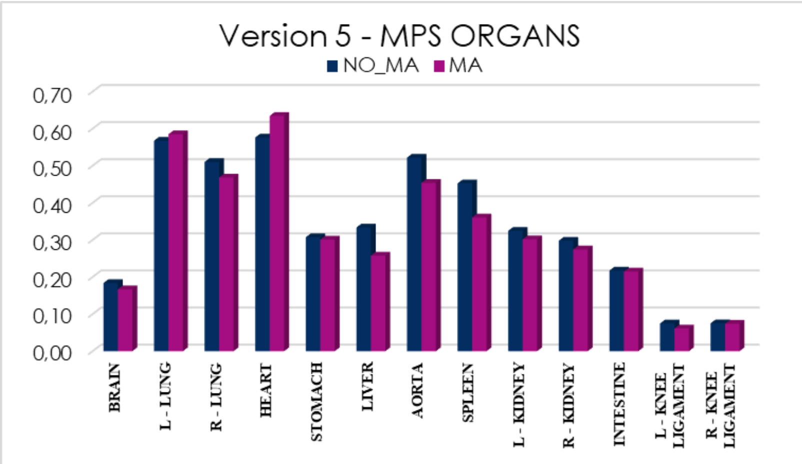


Figure 68 – MPS, Organs – THUMS v5 (w/out M_A) vs THUMS v5 (w/ M_A)

BONES	MPS	Injury Risk
SKULL	0,003906	0,20%
FACE	0,000679	0%
CERVICAL SPINE	0,00756	1,44%
THORACIC SPINE	0,009173	2,56%
LUMBER SPINE	0,011581	5,11%
L - CLAVICLE	0,002855	0,08%
R - CLAVICLE	0,001578	0,01%
STERNUM	0,003019	0,09%
L - SCAPULA	0,005682	0,61%
L - RIB [MAX = 01]	0,00226	0,04%
R - RIB [MAX = 01]	0,003679	0,17%
R - SCAPULA	0,004976	0,41%
L - HOMERUS	0,002145	0,03%
R - HOMERUS	0,003861	0,19%
L - FOREARM	0,002485	0,05%
R-FOREARM	0,002467	0,05%
SACRUM	0,002157	0,03%
L - PELVIS	0,014597	9,99%
R - PELVIS	0,00365	0,16%
L - FEMUR	0,002266	0,04%
R - FEMUR	0,002006	0,03%
L - LOWER LEG	0,001784	0,02%
R - LOWER LEG	0,00191	0,02%

Table 40 – Injury Risk Parameters, Bones – THUMS v6 (w/out M_A) Fall from Seated

Figure 69 – MPS and IR, Bones – THUMS v6 (w/out M_A) Fall from Seated

ORGANS	MPS	CSDM	IR – CSDM
BRAIN	0	0	0,00%
L – LUNG	0,148106	0	0%
R – LUNG	0,213175	0	0%
HEART	0,368293	0,016826	0%
STOMACH	1	0,03226	0,40%
LIVER	1	0,019505	0,16%
AORTA	0,166806	0	0,00%
SPLEEN	1	0,004961	0,01%
L – KIDNEY	0,495326	0,007174	0,03%
R – KIDNEY	0,455816	0,075136	1,83%
INTESTINE	0,598949	0,010801	0%
L - KNEE LIGAMENT	0,130557	0	0%
R - KNEE LIGAMENT	0,084676	0	0%

Table 41 – Injury Risk Parameters, Organs – THUMS v6 (w/out M_A) Fall from Seated

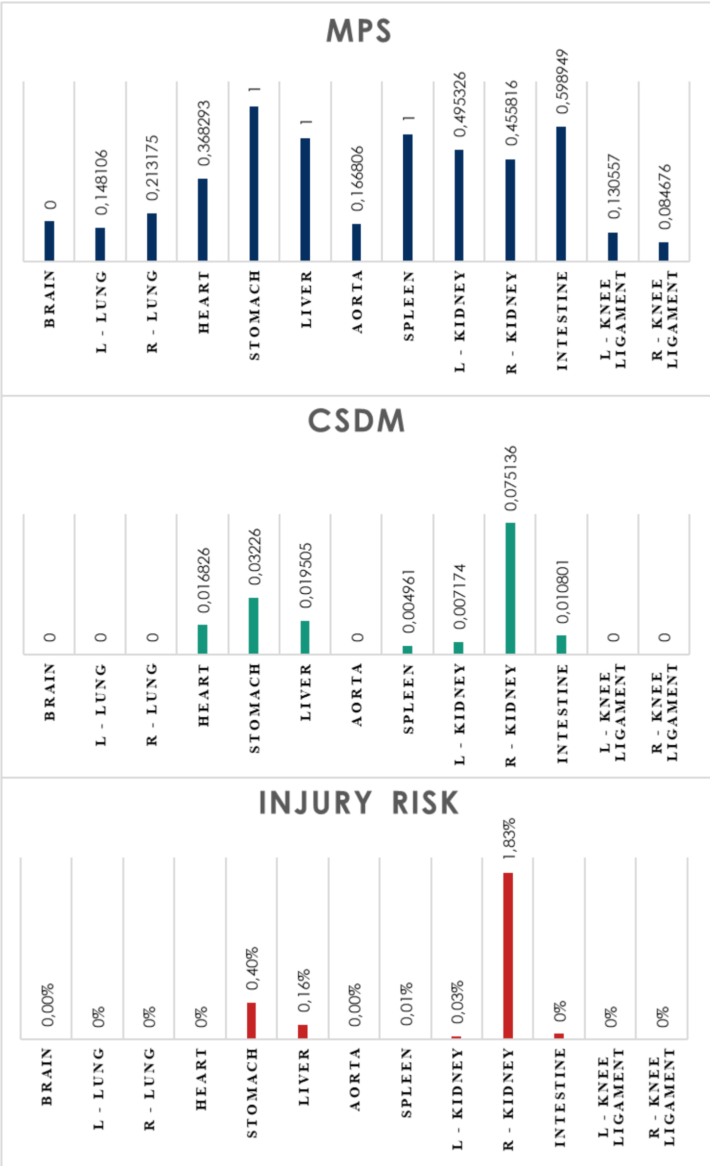


Figure 70 – MPS, CSDM and IR, Organs – THUMS v6 (w/out M_A) Fall from Seated

BONES	MPS	Injury Risk
SKULL	0,003438	0,13%
FACE	0,000899	0%
CERVICAL SPINE	0,008915	2,36%
THORACIC SPINE	0,007732	1,54%
LUMBER SPINE	0,007107	1,20%
L - CLAVICLE	0,00423	0,25%
R - CLAVICLE	0,001676	0,02%
STERNUM	0,002772	0,07%
L - SCAPULA	0,006788	1,04%
L - RIB [MAX = 01]	0,002839	0,08%
R - RIB [MAX = 01]	0,003107	0,10%
R - SCAPULA	0,004529	0,31%
L - HOMERUS	0,002105	0,03%
R - HOMERUS	0,003569	0,15%
L - FOREARM	0,001913	0,02%
R-FOREARM	0,00198	0,03%
SACRUM	0,002132	0,03%
L - PELVIS	0,013828	8,56%
R - PELVIS	0,003934	0,20%
L - FEMUR	0,002446	0,05%
R - FEMUR	0,001805	0,02%
L - LOWER LEG	0,001608	0,01%
R - LOWER LEG	0,001277	0,01%

Table 42 – Injury Risk Parameters, Bones – THUMS v6 (w/ M_A) Fall from Seated

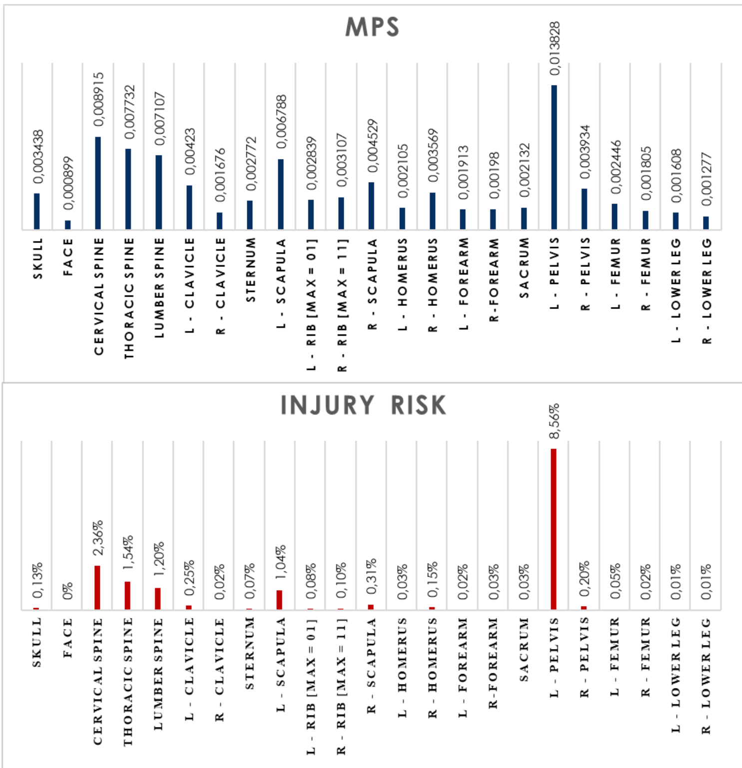


Figure 71 – MPS and IR, Bones – THUMS v6 (w/ M_A) Fall from Seated

ORGANS	MPS	CSDM	IR - CSDM
BRAIN	0	0	0,00%
L – LUNG	0,151376	0	0,00%
R – LUNG	0,188071	0	0,00%
HEART	0,370374	0,010967	0,00%
STOMACH	1	0,023283	0,22%
LIVER	0	0,019493	0,16%
AORTA	0,170044	0	0,00%
SPLEEN	0	0,002277	0,00%
L – KIDNEY	0,433936	0,004787	0,01%
R – KIDNEY	0,397377	0,014558	0,10%
INTESTINE	0,547696	0,005013	0,01%
L - KNEE LIGAMENT	0,118205	0	0,00%
R - KNEE LIGAMENT	0,068872	0	0,00%

Table 43 – Injury Risk Parameters, Organs – THUMS v6 (w/ M_A) Fall from Seated

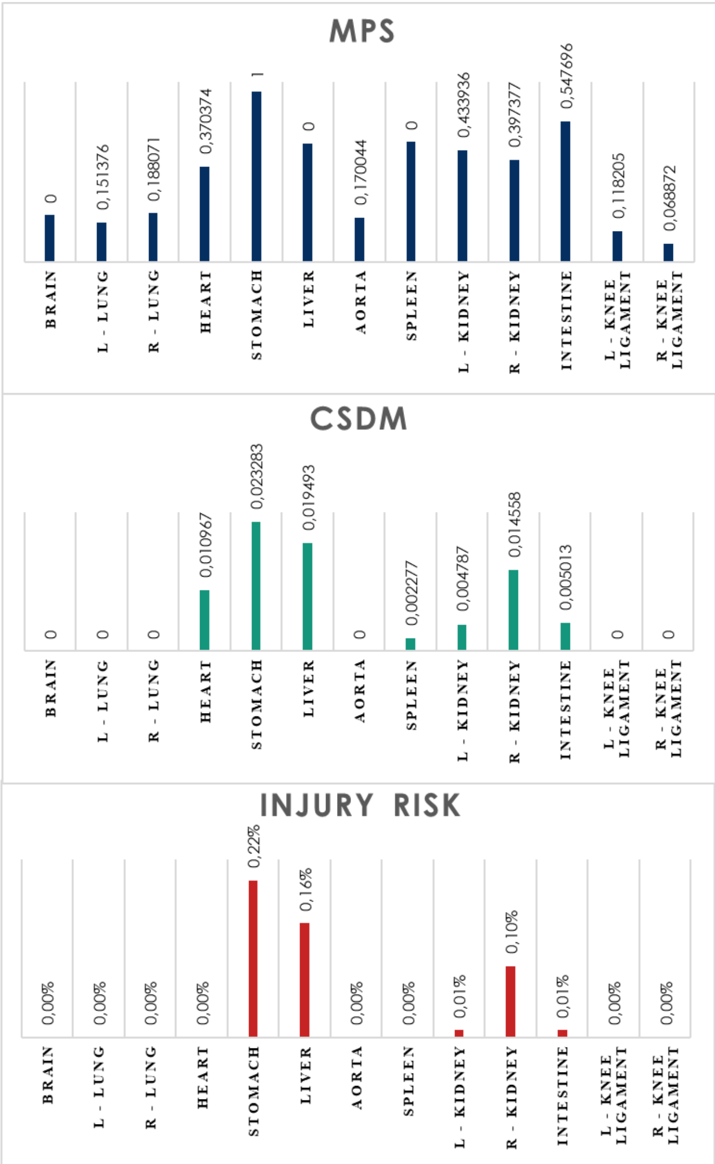


Figure 72 – MPS, CSDM and IR, Organs – THUMS v6 (w/ M_A) Fall from Seated

Version 6 w/out Muscle Activation vs Version 6 w/ Muscle Activation

MPS BONES	NO_MA	MA
SKULL	0,003906	0,003438
FACE	0,000679	0,000899
CERVICAL SPINE	0,00756	0,008915
THORACIC SPINE	0,009173	0,007732
LUMBER SPINE	0,011581	0,007107
L - CLAVICLE	0,002855	0,00423
R - CLAVICLE	0,001578	0,001676
STERNUM	0,003019	0,002772
L - SCAPULA	0,005682	0,006788
L - RIB [MAX = 03]	0,00226	0,002839
R - RIB [MAX = 12]	0,003679	0,003107
R - SCAPULA	0,004976	0,004529
L - HOMERUS	0,002145	0,002105
R - HOMERUS	0,003861	0,003569
L - FOREARM	0,002485	0,001913
R-FOREARM	0,002467	0,00198
SACRUM	0,002157	0,002132
L - PELVIS	0,014597	0,013828
R - PELVIS	0,00365	0,003934
L - FEMUR	0,002266	0,002446
R - FEMUR	0,002006	0,001805
L - LOWER LEG	0,001784	0,001608
R - LOWER LEG	0,00191	0,001277

Table 44 – MPS Bones – THUMS v6 w/out M_A vs THUMS v6 w/ M_A

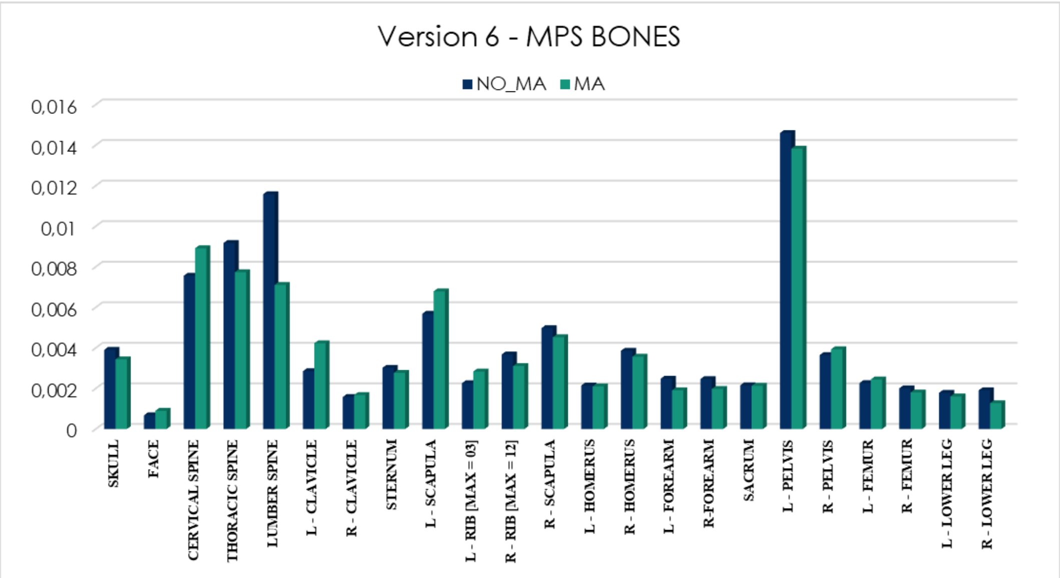


Figure 73 – MPS, Bones – THUMS v6 (w/out M_A) vs THUMS v6 (w/ M_A)

ORGANS	MPS NO_MA	MPS MA	CSDM NO_MA	CSDM MA
BRAIN	0	0	0	0
L - LUNG	0,148106	0,151376	0	0
R - LUNG	0,213175	0,188071	0	0
HEART	0,368293	0,370374	0,016826	0,010967
STOMACH	1	1	0,03226	0,023283
LIVER	1	0	0,019505	0,019493
AORTA	0,166806	0,170044	0	0
SPLEEN	1	0	0,004961	0,002277
L - KIDNEY	0,495326	0,433936	0,007174	0,004787
R - KIDNEY	0,455816	0,397377	0,075136	0,014558
INTESTINE	0,598949	0,547696	0,010801	0,005013
L - KNEE LIGAMENT	0,130557	0,118205	0	0
R - KNEE LIGAMENT	0,084676	0,068872	0	0

Table 45 – MPS, CSDM Organs – THUMS v6 w/out M_A vs THUMS v6 w/ M_A

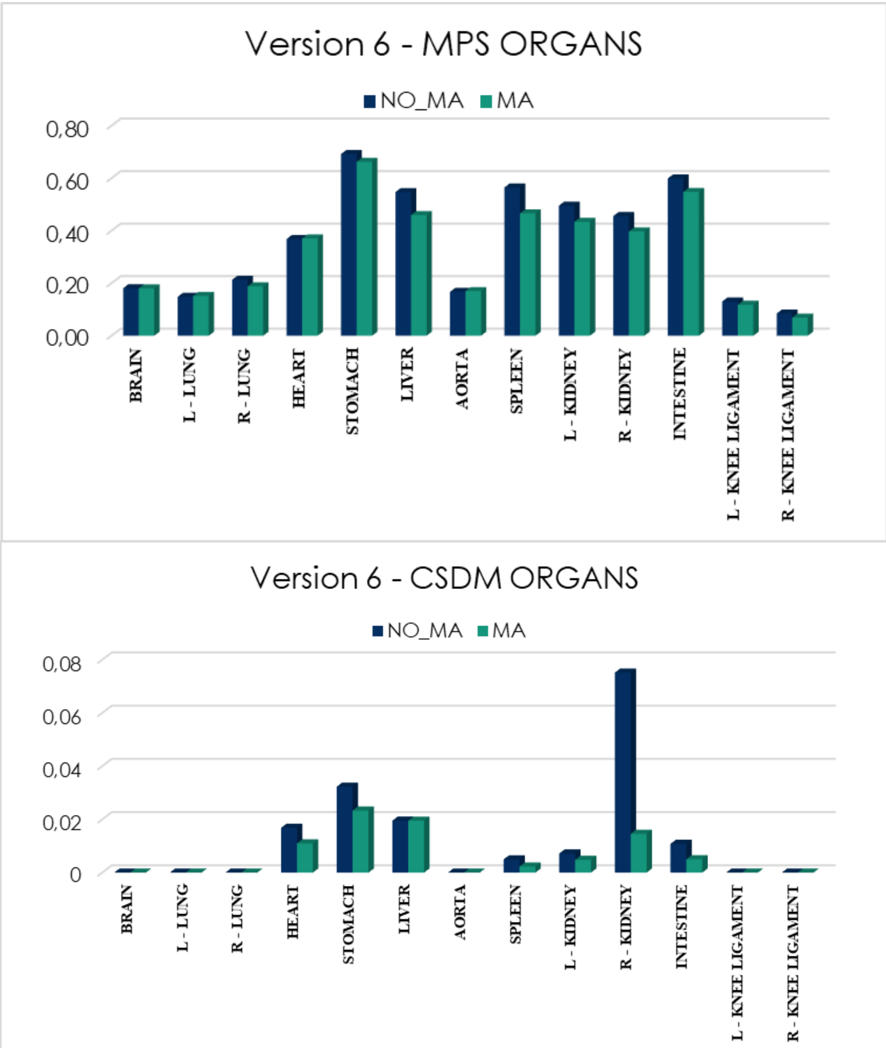


Figure 74 – MPS and CSDM, Organs – THUMS v6 (w/out M_A) vs THUMS v6 (w/ M_A)

Comparison between all Versions

MPS BONES	V4	V5	V5_MA	V6	V6_MA
SKULL	0,002666	0,001006	0,000833	0,003906	0,003438
FACE	0,000813	0,001628	0,001687	0,000679	0,000899
CERVICAL SPINE	0,004924	0,005854	0,00567	0,00756	0,008915
THORACIC SPINE	0,006021	0,048473	0,025471	0,009173	0,007732
LUMBER SPINE	0,002683	0,016008	0,01479	0,011581	0,007107
L – CLAVICLE	0,001952	0,06965	0,06922	0,002855	0,00423
R – CLAVICLE	0,000927	0,070586	0,088505	0,001578	0,001676
STERNUM	0,002552	0,016118	0,002593	0,003019	0,002772
L – SCAPULA	0,00353	0,002892	0,001876	0,005682	0,006788
L - RIB [MAX = 01]	0,003311	0,006944	0,007388	0,00226	0,002839
R - RIB [MAX = 12]	0,003989	0,025013	0,023807	0,003679	0,003107
R – SCAPULA	0,004813	0,002785	0,002533	0,004976	0,004529
L – HOMERUS	0,002415	0,004518	0,004863	0,002145	0,002105
R – HOMERUS	0,002154	0,005586	0,004542	0,003861	0,003569
L – FOREARM	0,001758	0,004368	0,00402	0,002485	0,001913
R-FOREARM	0,000837	0,006551	0,00417	0,002467	0,00198
SACRUM	0,001974	0,001456	0,001525	0,002157	0,002132
L – PELVIS	0,016359	0,038766	0,004048	0,014597	0,013828
R – PELVIS	0,00299	0,006142	0,004063	0,00365	0,003934
L – FEMUR	0,002978	0,003326	0,003384	0,002266	0,002446
R – FEMUR	0,001443	0,003666	0,003497	0,002006	0,001805
L - LOWER LEG	0,001636	0,000968	0,00092	0,001784	0,001608
R - LOWER LEG	0,001359	0,001062	0,001041	0,00191	0,001277

Table 46 – MPS Bones – THUMS v4 vs THUMS v5 vs THUMS v6

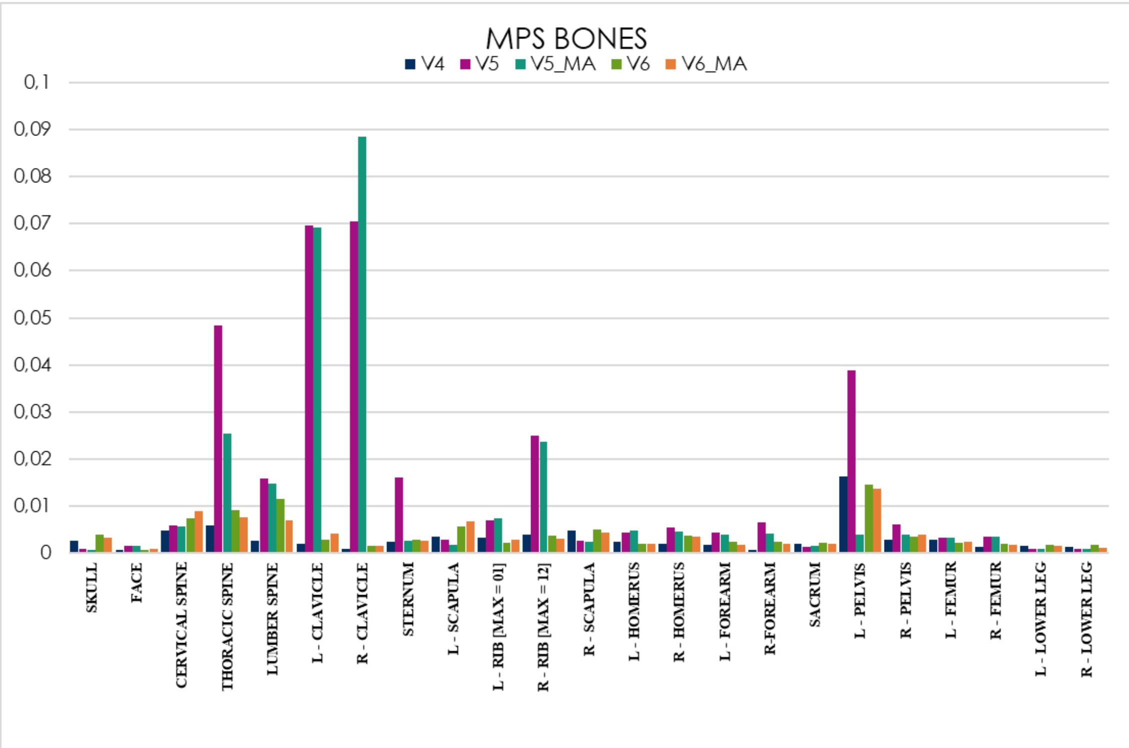


Figure 75 – MPS, Bones – THUMS v4 vs THUMS v5 vs THUMS v6

ORGANS	V4	V5	V5_MA	V6	V6_MA
BRAIN	0	0,090585	0	0	0
L - LUNG	0,166061	0,157899	0,186929	0,148106	0,151376
R - LUNG	0,229518	0,221305	0,218324	0,213175	0,188071
HEART	0,472448	0,195867	0,177257	0,368293	0,370374
STOMACH	1	0,194145	0	1	1
LIVER	1	0,147553	0	1	0
AORTA	0,167095	0,194925	0,182943	0,166806	0,170044
SPLEEN	0	0,176274	0	1	0
L - KIDNEY	0,306093	0,17573	0,129197	0,495326	0,433936
R - KIDNEY	0,382447	0,180916	0,147189	0,455816	0,397377
INTESTINE	0,530731	0,183479	0,179449	0,598949	0,547696
L - KNEE LIGAMENT	0,127159	0,038913	0,043978	0,130557	0,118205
R - KNEE LIGAMENT	0,082552	0,089941	0,043208	0,084676	0,068872

Table 47 – MPS Organs – THUMS v4 vs THUMS v5 vs THUMS v6

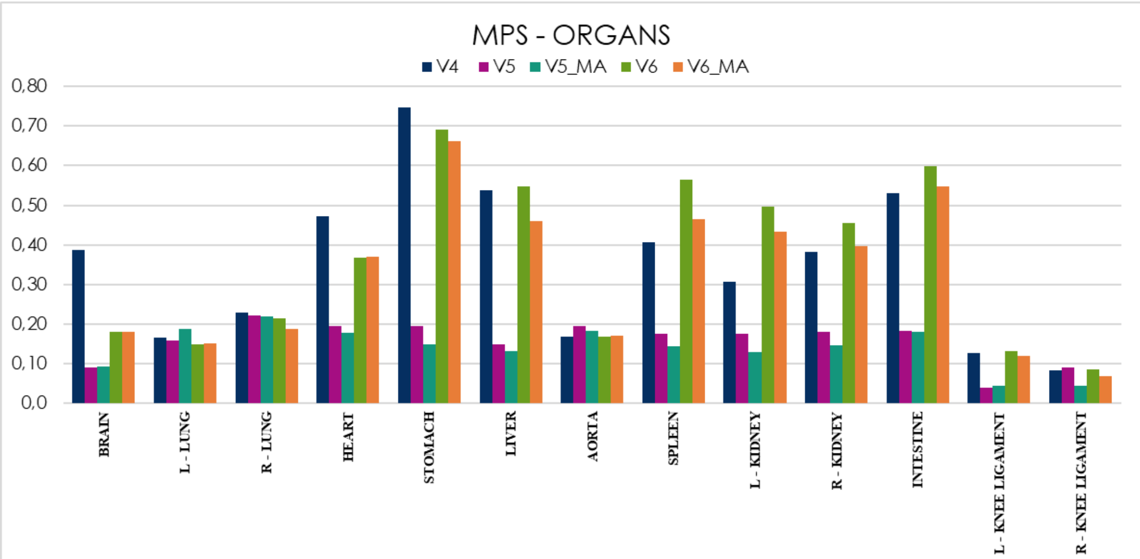


Figure 76 – MPS, Organs – THUMS v4 vs THUMS v5 vs THUMS v6

Third Scenario

BONES	MPS	Injury Risk
SKULL	0,05343	99%
FACE	0,03112	64%
CERVICAL SPINE	0,004884	0%
THORACIC SPINE	0,006046	0,74%
LUMBER SPINE	0,002381	0,04%
L - CLAVICLE	0,004346	0,27%
R - CLAVICLE	0,004419	0,29%
STERNUM	0,002598	0,06%
L - SCAPULA	0,010932	4,31%
L - RIB [MAX = 07]	0,009188	2,58%
R - RIB [MAX = 03]	0,006135	0,77%
R - SCAPULA	0,012247	6,02%
L - HOMERUS	0,003329	0,12%
R - HOMERUS	0,002948	0,09%
L - FOREARM	0,002624	0,06%
R-FOREARM	0,002615	0,06%
SACRUM	0,00826	1,88%
L - PELVIS	0,024894	40,90%
R - PELVIS	0,018399	19,06%
L - FEMUR	0,005188	0,47%
R - FEMUR	0,005717	0,62%
L - LOWER LEG	0,001892	0,02%
R - LOWER LEG	0,004384	0,28%

Table 48 – Injury Risk Parameters, Bones – THUMS v4 (Manually Manipulated) Fall from Standing

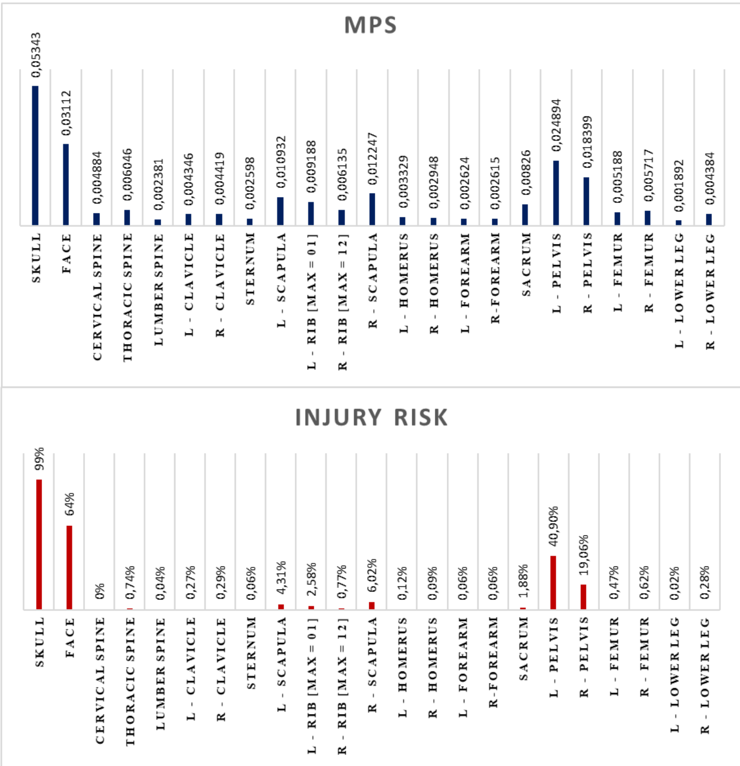


Figure 77 – MPS and IR, Bones – THUMS v4 (MM) Fall from Standing

ORGANS	MPS	CSDM	IR - CSDM
BRAIN	1	0,00179	0,00%
L - LUNG	0,433689	0,002473	0%
R - LUNG	0,2861	0,001092	0%
HEART	0,617961	0,524226	0%
STOMACH	1	0,280867	17,60%
LIVER	1	0,334849	23,14%
AORTA	0,260645	0,001205	0,00%
SPLEEN	1	0,528016	43,31%
L – KIDNEY	0,645393	0,575545	47,88%
R – KIDNEY	0,553872	0,397254	29,75%
INTESTINE	0,579497	0,10537	3%
L - KNEE LIGAMENT	0,158409	0	0%
R - KNEE LIGAMENT	0,143635	0	0%

Table 49 – Injury Risk Parameters, Organs – THUMS v4 (Manually Manipulated) Fall from Standing

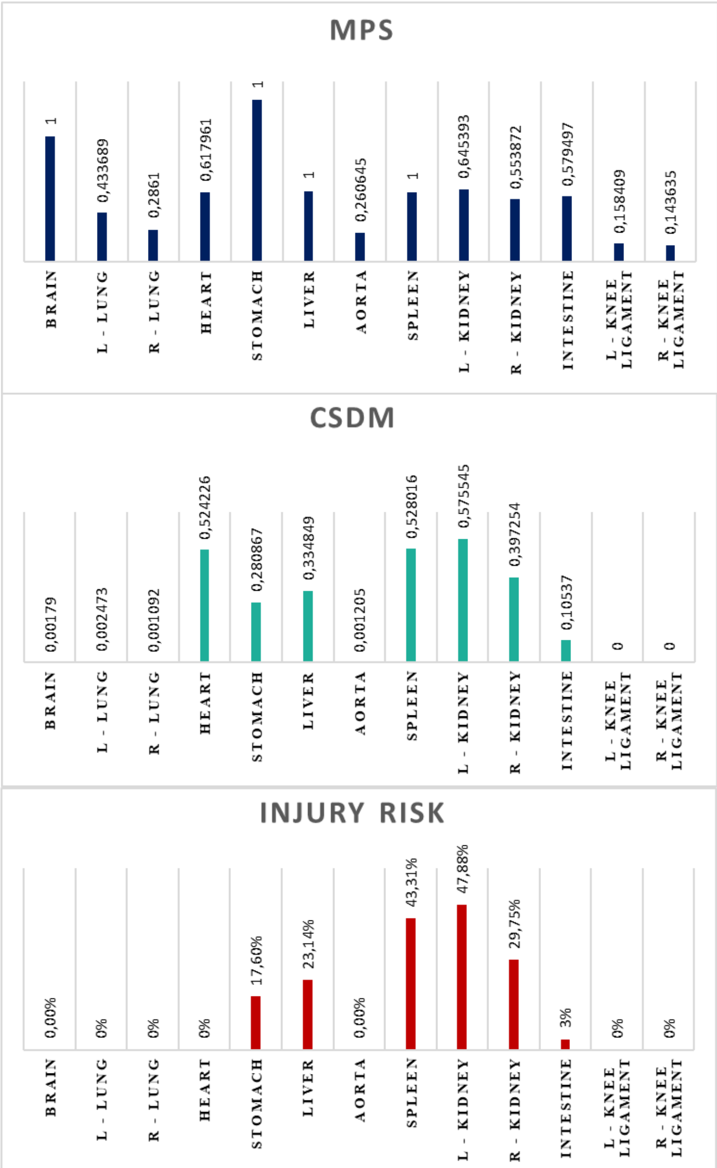


Figure 78 – MPS, CSDM and IR, Organs – THUMS v4 (MM) Fall from Standing

BONES	MPS	Injury Risk
SKULL	0,062783	100%
FACE	0,002768	0%
CERVICAL SPINE	0,012015	6%
THORACIC SPINE	0,011256	4,70%
LUMBER SPINE	0,005839	0,66%
L - CLAVICLE	0,002772	0,07%
R - CLAVICLE	0,003039	0,09%
STERNUM	0,00341	0,13%
L - SCAPULA	0,006613	0,96%
L - RIB [MAX = 06]	0,013388	7,79%
R - RIB [MAX = 06]	0,010743	4,09%
R - SCAPULA	0,006665	0,99%
L - HOMERUS	0,009254	2,63%
R - HOMERUS	0,008866	2,32%
L - FOREARM	0,004434	0,29%
R-FOREARM	0,004134	0,24%
SACRUM	0,003114	0,10%
L - PELVIS	0,016344	13,76%
R - PELVIS	0,01727	16,04%
L - FEMUR	0,009464	2,81%
R - FEMUR	0,010474	3,80%
L - LOWER LEG	0,008556	2,08%
R - LOWER LEG	0,008553	2,08%

Table 50 – Injury Risk Parameters, Bones – THUMS v4 (Provided by Toyota) Fall from Standing

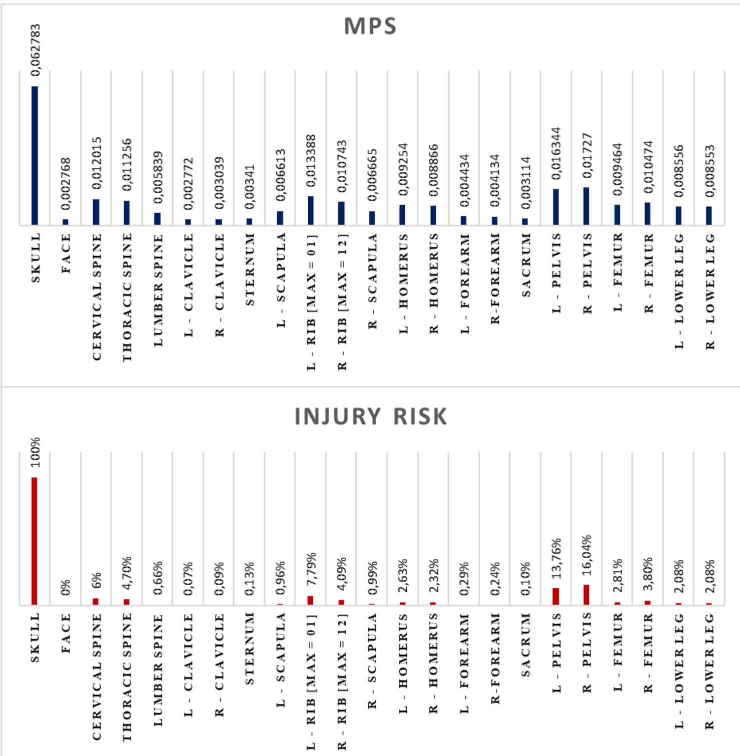


Figure 79 – MPS and IR, Bones – THUMS v4 (official) Fall from Standing

ORGANS	MPS	CSDM	IR - CSDM
BRAIN	1	0,018534	0,19%
L - LUNG	0	0	0%
R - LUNG	0	0	0%
HEART	1	0,923428	0%
STOMACH	1	0,91097	70,75%
LIVER	1	0,682445	57,04%
AORTA	0,841379	0,122924	4,36%
SPLEEN	1	0,54347	44,83%
L - KIDNEY	0,64314	0,909841	70,70%
R - KIDNEY	0,596734	0,813122	65,85%
INTESTINE	1	0,113473	4%
L - KNEE LIGAMENT	0,182954	0	0%
R - KNEE LIGAMENT	0,182139	0	0%

Table 51 – Injury Risk Parameters, Organs – THUMS v4 (Provided by Toyota) Fall from Standing

Figure 80 – MPS, CSDM and IR, Organs – THUMS v4 (official) Fall from Standing

BONES	MPS	Injury Risk
SKULL	0,03258	69%
FACE	0,008989	2%
CERVICAL SPINE	0,007051	1%
THORACIC SPINE	0,02106	27,22%
LUMBER SPINE	0,00734	1,32%
L - CLAVICLE	0,001861	0,02%
R - CLAVICLE	0,001908	0,02%
STERNUM	0,002366	0,04%
L - SCAPULA	0,004449	0,29%
L - RIB [MAX = 01]	0,003151	0,10%
R - RIB [MAX = 01]	0,003244	0,11%
R - SCAPULA	0,004214	0,25%
L - HOMERUS	0,002995	0,09%
R - HOMERUS	0,002724	0,07%
L - FOREARM	0,002255	0,04%
R-FOREARM	0,002089	0,03%
SACRUM	0,014744	10,28%
L - PELVIS	0,016394	1,64%
R - PELVIS	0,012555	6,47%
L - FEMUR	0,002655	0,06%
R - FEMUR	0,002723	0,07%
L - LOWER LEG	0,002176	0,03%
R - LOWER LEG	0,00221	0,04%

Table 52 – Injury Risk Parameters, Bones – THUMS v6 (Manually Manipulated) Fall from Standing

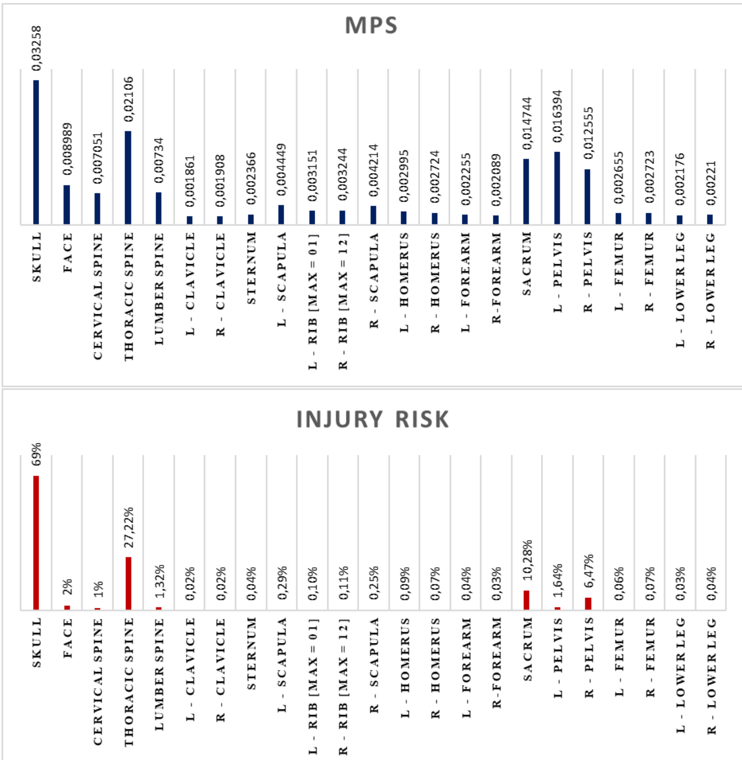


Figure 81 – MPS and IR, Bones – THUMS v6 (MM) Fall from Standing

ORGANS	MPS	CSDM	IR - CSDM
BRAIN	0	0,201778	0,92%
L - LUNG	0,164853	0	0%
R - LUNG	0,245856	0	0%
HEART	0,562812	0,533414	0%
STOMACH	1	0,087442	2,39%
LIVER	1	0,211748	11,09%
AORTA	0,221838	0	0,00%
SPLEEN	1	0,151164	6,25%
L - KIDNEY	0,67066	0,146179	5,90%
R - KIDNEY	0,612808	0,192392	9,44%
INTESTINE	1	0,119526	4%
L - KNEE LIGAMENT	0,079253	0	0%
R - KNEE LIGAMENT	0,078741	0	0%

Table 53 – Injury Risk Parameters, Organs – THUMS v6 (Manually Manipulated) Fall from Standing

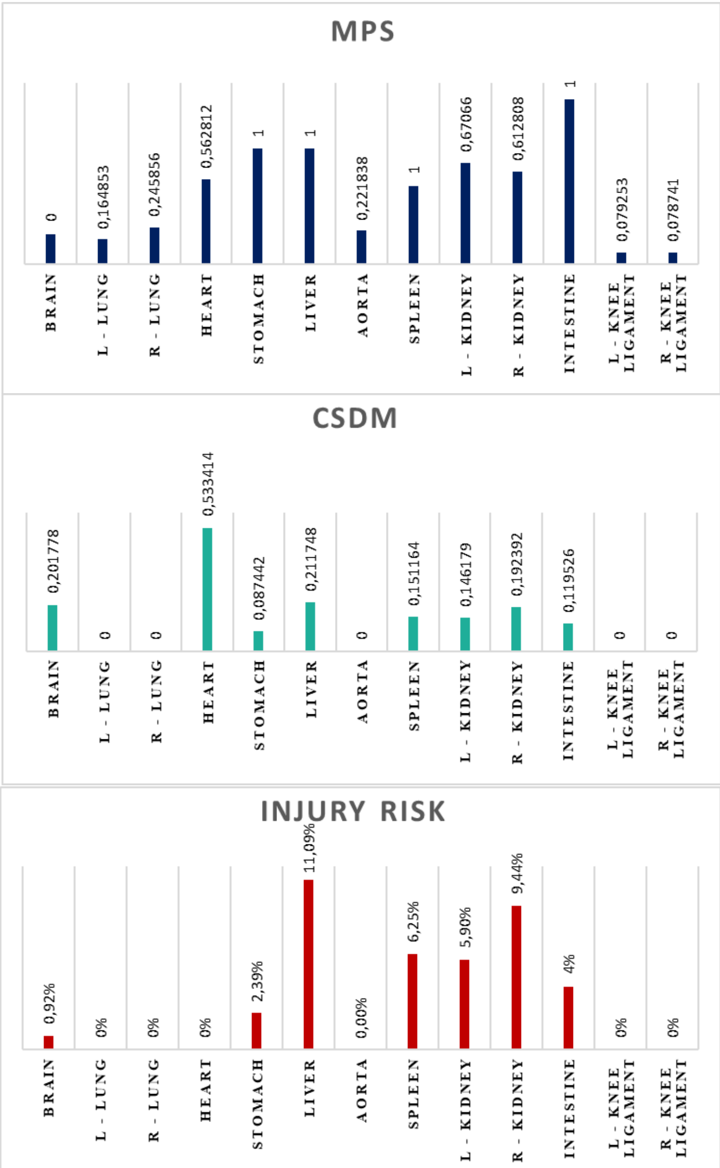


Figure 82 – MPS, CSDM and IR, Organs – THUMS v6 (MM) Fall from Standing

Comparison between all Versions

MPS BONES	V4_MM	V4_OFF	V6
SKULL	0,05343	0,062783	0,03258
FACE	0,03112	0,002768	0,008989
CERVICAL SPINE	0,004884	0,012015	0,007051
THORACIC SPINE	0,006046	0,011256	0,02106
LUMBER SPINE	0,002381	0,005839	0,00734
L - CLAVICLE	0,004346	0,002772	0,001861
R - CLAVICLE	0,004419	0,003039	0,001908
STERNUM	0,002598	0,00341	0,002366
L - SCAPULA	0,010932	0,006613	0,004449
L - RIB [MAX = 07]	0,009188	0,013388	0,003151
R - RIB [MAX = 03]	0,006135	0,010743	0,003244
R - SCAPULA	0,012247	0,006665	0,004214
L - HOMERUS	0,003329	0,009254	0,002995
R - HOMERUS	0,002948	0,008866	0,002724
L - FOREARM	0,002624	0,004434	0,002255
R-FOREARM	0,002615	0,004134	0,002089
SACRUM	0,00826	0,003114	0,014744
L - PELVIS	0,024894	0,016344	0,016394
R - PELVIS	0,018399	0,01727	0,012555
L - FEMUR	0,005188	0,009464	0,002655
R - FEMUR	0,005717	0,010474	0,002723
L - LOWER LEG	0,001892	0,008556	0,002176
R - LOWER LEG	0,004384	0,008553	0,00221

Table 53 – MPS Bones – THUMS v4 vs THUMS v6

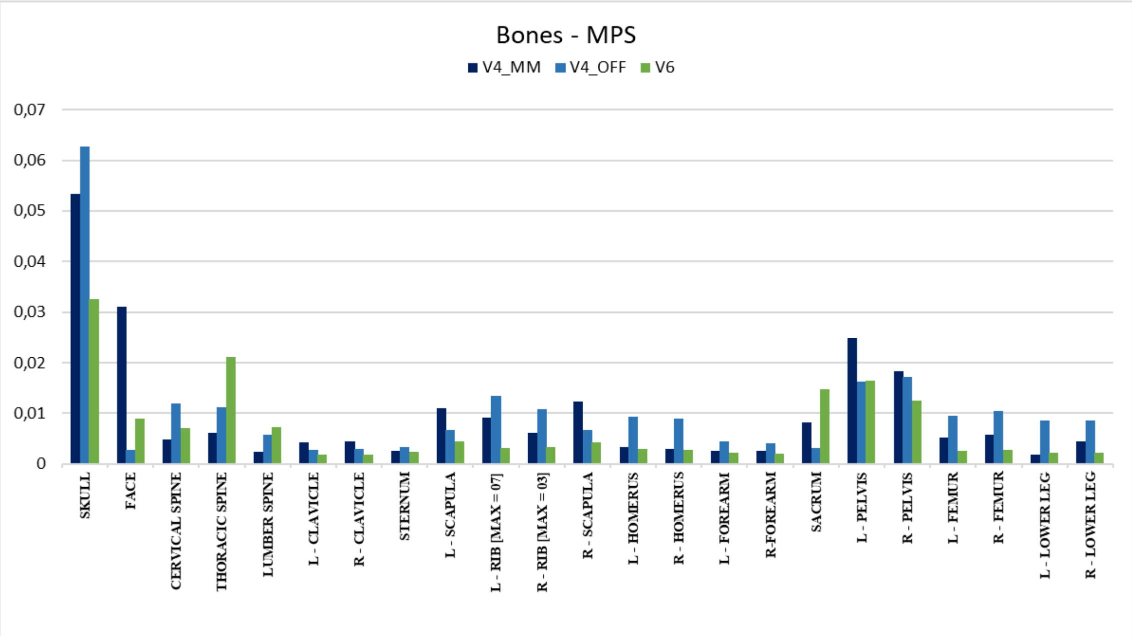


Figure 83 – MPS, Bones – THUMS v4 vs THUMS v6

MPS ORGANS	V4_MM	V4_OFF	V6
BRAIN	1	1	0
L - LUNG	0,433689	0	0,164853
R - LUNG	0,2861	0	0,245856
HEART	0,617961	1	0,562812
STOMACH	1	1	1
LIVER	1	1	1
AORTA	0,260645	0,841379	0,221838
SPLEEN	1	1	1
L - KIDNEY	0,645393	0,64314	0,67066
R - KIDNEY	0,553872	0,596734	0,612808
INTESTINE	0,579497	1	1
L - KNEE LIGAMENT	0,158409	0,182954	0,079253
R - KNEE LIGAMENT	0,143635	0,182139	0,078741

Table 54 – MPS, Organs – THUMS v4 vs THUMS v6

CSDM ORGANS	V4_MM	V4_OFF	V6
BRAIN	0,00179	0,018534	0,201778
L - LUNG	0,002473	0	0
R - LUNG	0,001092	0	0
HEART	0,524226	0,923428	0,533414
STOMACH	0,280867	0,91097	0,087442
LIVER	0,334849	0,682445	0,211748
AORTA	0,001205	0,122924	0
SPLEEN	0,528016	0,54347	0,151164
L - KIDNEY	0,575545	0,909841	0,146179
R - KIDNEY	0,397254	0,813122	0,192392
INTESTINE	0,10537	0,113473	0,119526
L - KNEE LIGAMENT	0	0	0
R - KNEE LIGAMENT	0	0	0

Table 55 – CSDM, Organs – THUMS v4 vs THUMS v6

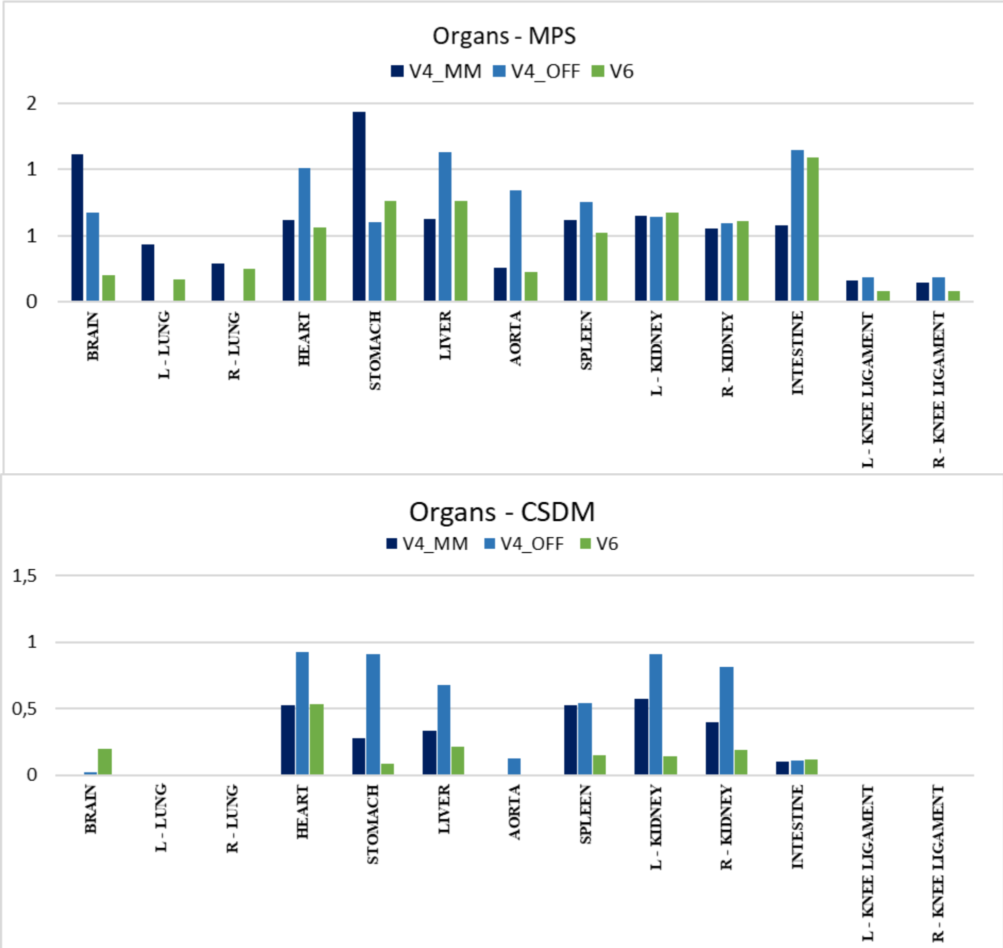


Figure 84 – MPS and CSDM, Organs – THUMS v4 vs THUMS v6

11. References

1. Toyota. *THUMS – Total Human Model for Safety*. https://global.toyota/en/newsroom/corporate/32665896.html

2. World Health Organization (WHO). *Road Traffic Injuries*. https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries/

3. Fahse, N., Millard, M., Kempter, F., Maier, S., Roller, M., & Fehr, J. (2023). Dynamic human body models in vehicle safety: An overview. *GAMM Journal of Applied Mathematics*, 43(3), Article 202300007. https://doi.org/10.1002/gamm.202300007

4. J. H. Lee, C. S. Kim, and M. W. Lee, "Comparison of Physical and Virtual Crash Test Dummies for Automotive Safety Evaluations," *International Journal of Automotive Technology*

5. Iwamoto M, Nakahira Y, Kimpara H. Development and Validation of the Total HUman Model for Safety (THUMS) Toward Further Understanding of Occupant Injury Mechanisms in Precrash and During Crash. Traffic Inj Prev. 2015;16 Suppl 1:S36-48. doi: 10.1080/15389588.2015.1015000. PMID: 26027974.

6. TOYOTA MOTOR CORPORATION & TOYOTA CENTRAL R&D LABS., INC., *THUMS AM50 V4.1 Documentation* [PDF].

7. TOYOTA MOTOR CORPORATION & TOYOTA CENTRAL R&D LABS., INC., *THUMS AM50 V5.3 Documentation* [PDF].

8. TOYOTA MOTOR CORPORATION & TOYOTA CENTRAL R&D LABS., INC., *THUMS AM50 V6.1 Documentation* [PDF].

9. Kato, D., Nakahira, Y., Iwamoto, M. (2017), A Study of Muscle Control with Two Feedback Controls for Posture and Reaction Force for More Accurate Prediction of Occupant Kinematics in Low-Speed Frontal Impacts, 25th ESV Conference, Paper Number 17-0004-O.

10. JSOL Corporation, *THUMS IRV Tool Workflow*, JMAG-Designer Ver.22.1 Release, 21 Oct. 2022. https://www.jsol-cae.com/en/news/2022/release/1021a.html.

11. Vezin, P., Bruyère, K., Bermond, F. (2001), Comparison of head and thorax cadaver and Hybrid III responses to a frontal sled deceleration for the validation of a car occupant mathematical model, Paper presented at: 17th ESV Conference; June 4-7, Amsterdam, The Netherlands.